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Design, Fabrication and Testing of the Air-Jet Oil Boom

Hydronautics, Inc, Laurel, MD

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Design, Fabrication and Testing of the Air-Jet Oil Boom

Interagency Energy/Environment R&D Program Report

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The key operational feature is a continuous, horizontally oriented air jet ejected from along the boom at the water's surface. Overall, each boom module is about 33 feet long and 2 feet in diameter. Major components include two inflatable sections (ducts) to support the continous air-jet nozzle and a center support float/jet pump. Some unique features of the structural design are low draft (1 inch) and excellent compliance to waves. Furthermore, the sections are both lightweight and highly compactible for storage.

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DESIGN, FABRICATION AND TESTING OF THE AIR-JET OIL BOOM

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CINCINNATI, OHIO 45268

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes performance evaluation tests of a research prototype Air-Jet Boom. The principle shows promise of performing effectively at relatively high water current speeds, thereby making spill cleanup possible in currents that normally cause conventional booms to fail. This technique will be of interest to all those concerned with cleaning up oil spills in inland and coastal waters. Further information may be obtained through the Resource Extraction and Handling Division, Oil and Hazardous Materials Spills Branch, Edison, New Jersey.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This report describes the design, fabrication and testing of the Air-Jet Boom; a novel boom which has the capability to divert oil slicks under wave and current conditions that normally preclude the deployment of conventional booms. Tests at the EPA's OHMSETT facility have demonstrated that this boom can, for example, successfully divert oil slicks at 3 knots with 85 percent efficiency when at 30 degrees to the flow. Moreover, with the addition of steep, 4-foot waves, the boom's performance is virtually unchanged.

The key operational feature is a continuous, horizontally oriented air jet ejected from along the boom at the water's surface. The flow interaction and the ensuing momentum transfer from the air jet to the water surface (by viscous and turbulent shear stress) induce a strong local surface current just ahead of the boom. When the boom is deployed at an angle to the flow (diversionary mode), the induced current causes the oncoming oil slick to be deflected and transported across the water's surface and apart from the clean, underlying flow.

Overall, each boom module is about 33 feet long and 2 feet in diameter. Major components include two inflatable sections (ducts) to support the continuous air-jet nozzle; and a center support float/jet pump arrangement to supply the high-volume, low-pressure (23,000 standard cubic feet/minute, at 3 inches of water) air flow required for operation. Some unique features of the structural design are low draft (1 inch) and excellent compliance to waves. Furthermore, the sections are both lightweight and highly compactible for storage.

This report was submitted in fulfillment of Contract No. 68-03-2497 by HYDRONAUTICS, Incorporated under the sponsorship of the U. S. Environmental Protection Agency. The report covers a period from January 1977 to January 1978 and was completed as of July 1978.

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SYMBOLS AND ABBREVIATIONS

A	cross sectional area, in.^{2}
A_o	projected area, ft^2
B_n	vibration coefficient, dimensionless
C_D	drag coefficient, dimensionless
c	conversion factor, .036 pounds/inch^2
D_a	drag, aerodynamic, pounds/foot
D_H	drag, hydrodynamic, pounds/foot
E	modulus of elasticity, pounds/inch^2
F	weight of end plate, pounds
f	thickness of the fabric, inches
F_L	lateral natural frequency, undamped, cycles per second
F_T	torsional natural frequency, undamped, cycles per second
G	gallons of oil distributed, shear modulus, pounds/inch^2
g_c	gravitational constant, feet/second^2
h	height of the nozzle from the free surface, inches
I	moment of inertia of the inflatable section, inches^4
J	polar moment of inertia, inches ^{4}
L	length of the boom, overall, feet
L_A	lift, aerodynamic, pounds/foot
L_H	lift, hydrodynamic, pounds/foot
ℓ	nozzle throat size, inches
ℓ_1	length of the inflatable section, inches
M	nozzle reaction moment, inch-pounds/foot
M_v	jet momentum, pounds/foot
m	uniform moment, inch-pounds/foot
$N_{x,y}$	nozzle reaction forces, pounds/foot
P	jet pump inlet pressure, pounds/inch^2
p	internal boom air pressure, inches of water

Q	compressor flow, SCFM
q	air-jet flow, SCFM
r	radius of boom, inches
S	wetted area, feet
SCFM	standard cubic feet/minute
T	time of oil distribution, seconds
t_o	average slick thickness upstream, millimeters
t_1	local slick thickness at the boom, millimeters
U	maximum air velocity at the free surface, feet/second
V	tow speed, current, feet/second
v	induced current velocity, feet/second
W	weight per unit length, pound/feet
y	lateral deflection, inches
α	air-jet impingement angle, degrees
δ	induced current depth, inches
ρ_A	density, air, pounds/feet^3
ρ_F	density, fabric, ounces/yard^2
ρ_W	density, water, pounds/feet^3
φ	torsional deflection, radians
θ	boom, deployment angle measured from the direction of flow, degrees
σ_a	axial membrane stress, pounds/inch^2
σ_c	circumferential membrane stress, pounds/inch^2
ξ	uniform vertical load, pounds/foot
ω	uniform horizontal load, pounds/foot

ACKNOWLEDGMENTS

We would like to extend our sincere thanks to John S. Farlow, EPA Project Officer for his support and cooperation throughout this work. Our appreciation also goes to the engineers, technicians and staff of OHMSETT for a fine job in conducting the Proof and Performance Tests, especially Bob Ackerman, Hank Lichte, Mike Johnson, Sol Schwartz and Robert Dickson.

SECTION 1

INTRODUCTION

BACKGROUND

An important strategy in the control of an oil spill is containment. Without containment, oil will spread over large distances, affecting areas well beyond the spill site. Floating oil booms, usually characterized by a vertical barrier extending above and below the water surface, as shown in Figure 1a, are routinely used for containment. While conventional booms are effective in calm water, experience shows that they do not work well in fast currents or high waves. Several investigators studying the performance of conventional booms concluded that oil loss increases quite rapidly with increasing currents greater than approximately 1 knot, and wave action decreased this limit further (1,2)*.

Oil loss can be reduced, however, by angling booms into the flow, thereby reducing the normal velocity component (relative to the boom axis) below 1 knot. In this configuration, booms do not actually contain the oil, but rather redirect or divert the flow of oil on the water surface apart from the clean bulk flow. For example, when a spill occurs on a fast-moving river, oil can be diverted to a quiescent area along the shoreline where it may be recovered by suitable skimmers, as shown in Figure 1b.

Performance testing of several commercially available booms in the diversionary configuration at the Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) has shown that the current for which there is no loss may be increased from 1.0 knots to 1.6 knots (in calm water), when a boom is deployed at 30 degrees to the flow (3). With the addition of 1-foot high regular waves with 1.5 second period, the no-loss speed was reduced to about 0.5 knot. Furthermore, of all the booms tested, none could remain upright or stable beyond a 2.0 knot current; containment failures occurred either from splashover or severe inclination from the vertical position (planing or diving).

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*Refer to References given on page 84.

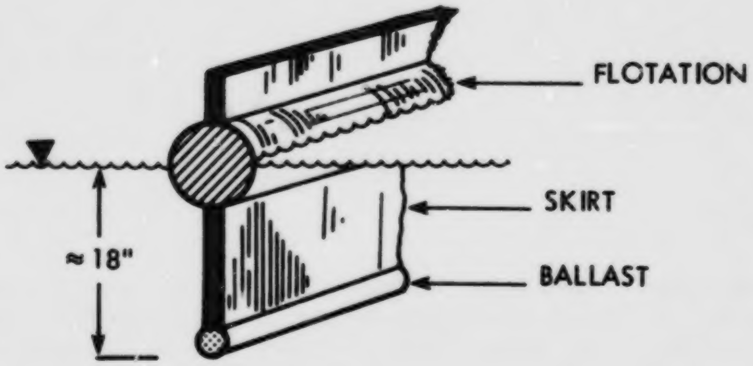

FLOTATION
SKIRT
BALLAST
≈ 18"

Figure 1a. Cross section of a conventional oil boom (typical)

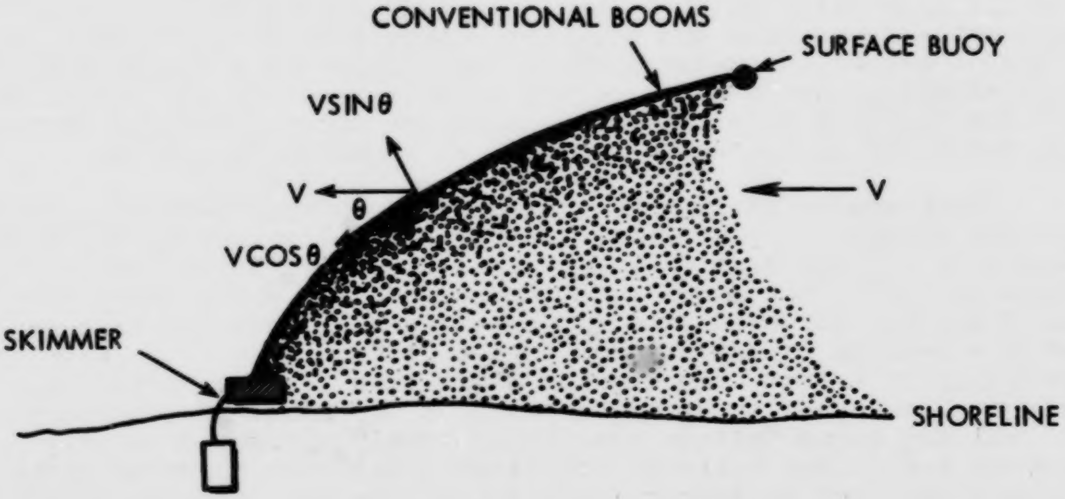

CONVENTIONAL BOOMS
SURFACE BUOY
VSINθ
V
θ
V
VCOSθ
SKIMMER
SHORELINE

Figure 1b. Deployment of a conventional oil boom in currents greater than one knot (typical)

Advanced Concepts

Because currents in excess of 2.0 knots are quite common on inland waterways prone to oil spills (i.e., precluding the use of conventional booms), the Environmental Protection Agency has sponsored several studies to investigate and demonstrate the feasibility of various high-current boom concepts.

In one of the more recent studies, a rigid, perforated plate, diversionary oil boom was developed and demonstrated (4). In principle, the boom is a floating baffle arrangement which slows down the surface flow, allowing oil to be contained and recovered in a quiescent area of the boom, as shown in Figure 2a. Tests at OHMSETT demonstrated that the performance of the rigid boom was markedly better than that of the conventional booms. The rigid boom is capable of diverting oil (1-millimeter slick) at 3.0 knots with less than 15 percent loss when deployed at 45 degrees to the flow; but, as noted in the study, use of this boom should be limited to situations with wave heights less than 1 foot. Moreover, because of high drag forces inherent in the concept and the sturdy moorings required, as shown in Figure 2b, the boom is best suited for permanent deployment at predetermined (i.e., high risk) locations.

The present study, also sponsored by the Environmental Protection Agency, resulted in the development of the Air-Jet Boom; this is a unique diversionary device which relies on the interaction of a high velocity air jet with the oil floating on the free surface. The prototype boom is shown in Figure 3 with a key for the principle elements. A detailed description of the boom is presented in Section 4.

Conclusions and Recommendations derived from the present study follows in Sections 2 and 3, respectively. Details of the development program, supporting design analyses, OHMSETT proof tests and OHMSETT performance tests are described in subsequent sections. A discussion of results presented in Section 10 concludes the report.

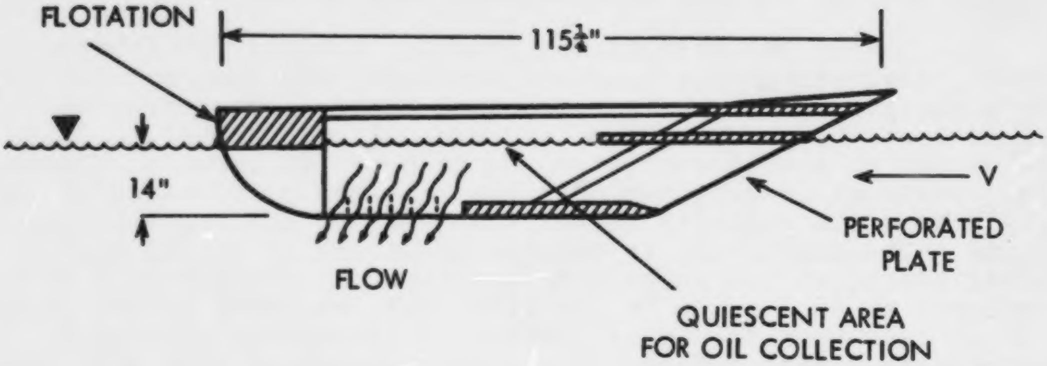

FLOTATION
115¾"
14"
FLOW
V
PERFORATED PLATE
QUIESCENT AREA FOR OIL COLLECTION

Figure 2a. General cross section of rigid perforated plate boom (from Reference 4).

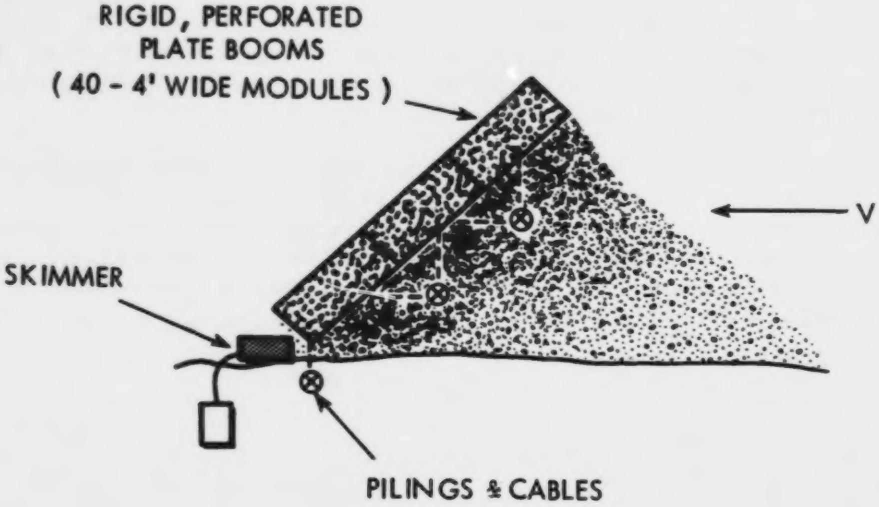
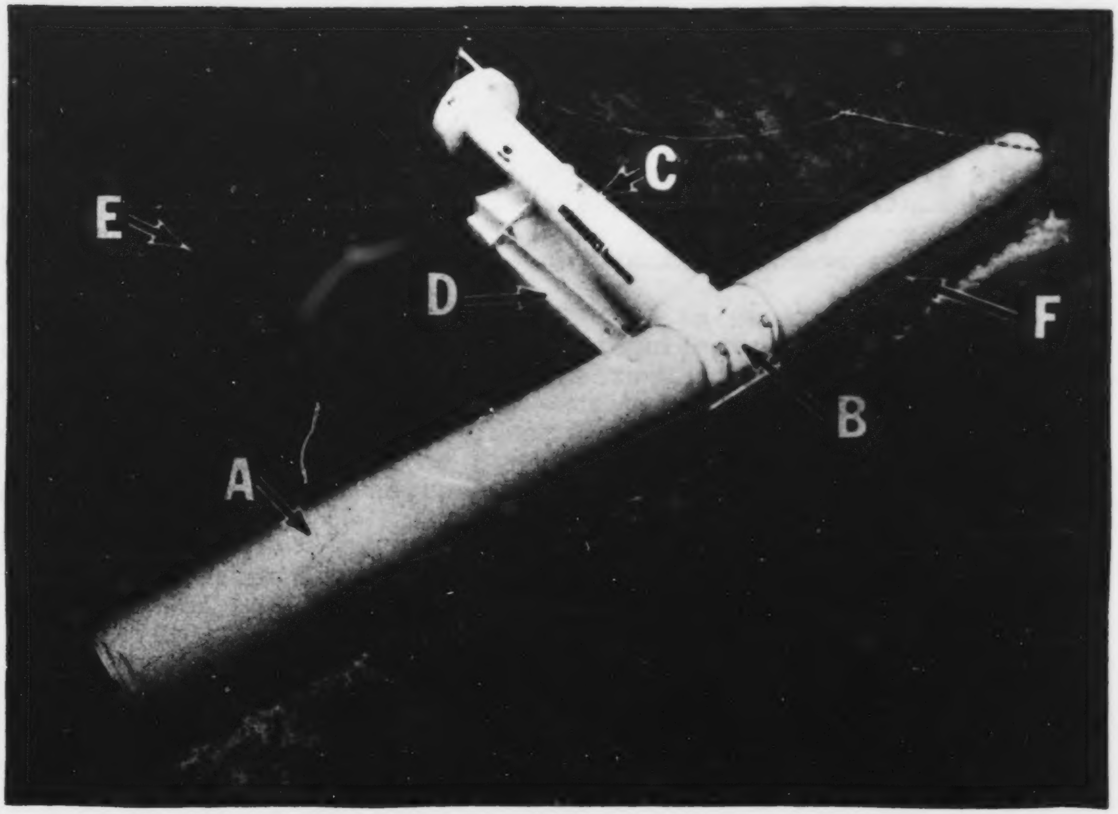

RIGID, PERFORATED PLATE BOOMS (40 - 4' WIDE MODULES)
V
SKIMMER
PILINGS & CABLES

Figure 2b. Proposed deployment of the rigid perforated plate boom (from Reference 4).



A - INFLATABLE SECTIONS
B - CENTER SECTION
C - JET PUMP
D - SUPPORT FLOAT
E - COMPRESSOR AIR SUPPLY HOSE
F - CONTINUOUS AIR JET NOZZLE

Figure 3. A view of the 10 meter long Air–Jet Boom.

SECTION 2

CONCLUSIONS

The Air-Jet Boom has the potential to provide an effective means of controlling oil slicks on inland waterways under conditions that normally preclude successful deployment of commercially available booms or other recently developed prototypes.

Performance tests at OHMSETT have shown that the Air-Jet Boom is capable of diverting thin oil slicks (2 millimeter) in 3.0 knot currents with 15 percent loss when deployed at 30 degrees to the flow. Moreover, the addition of waves has only a nominal effect on performance; steep, irregular waves (up to 4 feet high) increased losses by only 5 to 10 percent compared to experience in calm water, and in some cases there was no perceptible increase.

Additional operational features that distinguish the Air-Jet Boom from other booms are its shallow draft and low drag. The shallow draft is significant in two ways: first, floating debris is readily swept beneath the boom without snagging, and second, the boom can be deployed over shoals or in shallow streams where conventional booms will not even float. Low drag means that rigging and deployment is somewhat easier and that the natural tendency to form a catenary planform shape, which hinders diversion performance with conventional booms, is less pronounced.

The Air-Jet Boom features unique capabilities for diverting oil spills in fast current and waves. It relies upon a shore-based compressor to supply air, however, which restricts the choice of deployment sites to those having reasonable road access for the compressor(s). Of course, skimming gear and recovered oil storage tanks have the same type of limitation, so a spill recovery system using an Air-Jet Boom for slick diversion should not be unduly handicapped in this regard. Consideration should also be given to the length of air-supply hose that will be needed to reach from the compressor to the boom, as the pressure drop in an excessively long hose will cause a falloff in boom performance.

SECTION 3

RECOMMENDATIONS

A single 10-meter length of the Air-Jet Boom was demonstrated to be effective under simulated environmental conditions; ultimately, several adjoining lengths of boom should be tested in the field to confirm feasibility from a standpoint of practicality and compatibility with other oil spill control equipment. Prior to field demonstrations, however, two preliminary tasks should be undertaken:

Task 1 - The prototype version of the boom should be redesigned with particular regard to developing a lightweight, field deployable unit with improved hull form and simplified rigging for multiple-boom-length applications. At least two, and preferably three, booms should be fabricated.

Task 2 - The improved booms should be tested at OHMSETT to evaluate performance, seakeeping characteristics and/or limitations arising from multiple boom deployment. Special attention should be given to: the effect of slick thickening on performance of the downstream booms, and the optimum spacing and arrangement of adjacent booms, including the effect of staggering booms one behind another to improve diversion efficiency.

Task 3 - Following OHMSETT tests, the booms should be demonstrated in the field under realistic operating conditions using a real spill scenario. A suitable location for deployment might be a shallow (2 to 3 feet), fast-moving river (2 to 3 knots) less than a few hundred feet wide.

Other developmental projects that should be considered concern promising alternative uses and/or configurations of the Air-Jet Boom. One involves two booms deployed in a V-configuration ahead of an oil recovery vessel (such as the high-speed U. S. Coast Guard ZRV Skimmer) in order to concentrate the flow of oil into the skimming area and, thereby, increase the effective width of the system. A deck-mounted blower could supply the required air flow. A second developmental project that should be considered is the use of alternate air-supply systems that greatly reduce the boom's power requirements compared to the present compressor/jet pump design. One concept with high potential is a boom-mounted blower that might be either gas-engine driven or remotely by hydraulic power.

SECTION 4

DESCRIPTION

GENERAL

The Air-Jet Boom is shown in Figure 3 and is composed of two inflatable sections that extend from a rigid center section, a compressor-operated jet pump and its support float*. A significant feature is the continuous air-jet nozzle formed by the inflatable and center sections. The nozzle, oriented with the free surface as indicated in Figure 4, directs a high velocity jet of air flow at the air/water interface along the length of the boom. The resulting shear stress at the interface induces a local surface current; when the boom is deployed at an angle to the flow, a thin oncoming oil slick is deflected and transported by this current across the surface, apart from the underlying bulk flow of clean water. The oil's trajectory is indicated in Figure 5 where "complete" diversion is being affected in calm (only small wind-waves) water.

When the boom encounters waves, the induced surface current is generally undiminished because the inflatable sections are compliant and thus conform to the wave contours maintaining the necessary air-jet orientation. Figure 6 illustrates how well the inflatable section negotiates steep, 4-foot high (crest to trough), irregular waves. In some cases, however, the sections do not conform and form a "bridge" across adjacent wave crests (i.e., in short wavelength waves, see Figure 6b); the air jet will retain a degree of effectiveness even though it is extended from the free surface for a short period of time.**

Air Supply

The low pressure, high volume of air flow that is required for a single air-jet boom is delivered by means of a jet pump which expands and augments the air flow supplied by a high pressure air compressor. To achieve the boom's rated performance, a standard, 750 SCFM, commercial grade air compressor will deliver about 23,000 SCFM at 3 inches of water (see Figure 7). Smaller compressors can be used, but with reduced diversion performance.

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*Design and assembly drawings are given in Appendix A.

**Results from the OHMSETT Performance Tests are summarized in Tables 4 and 5.

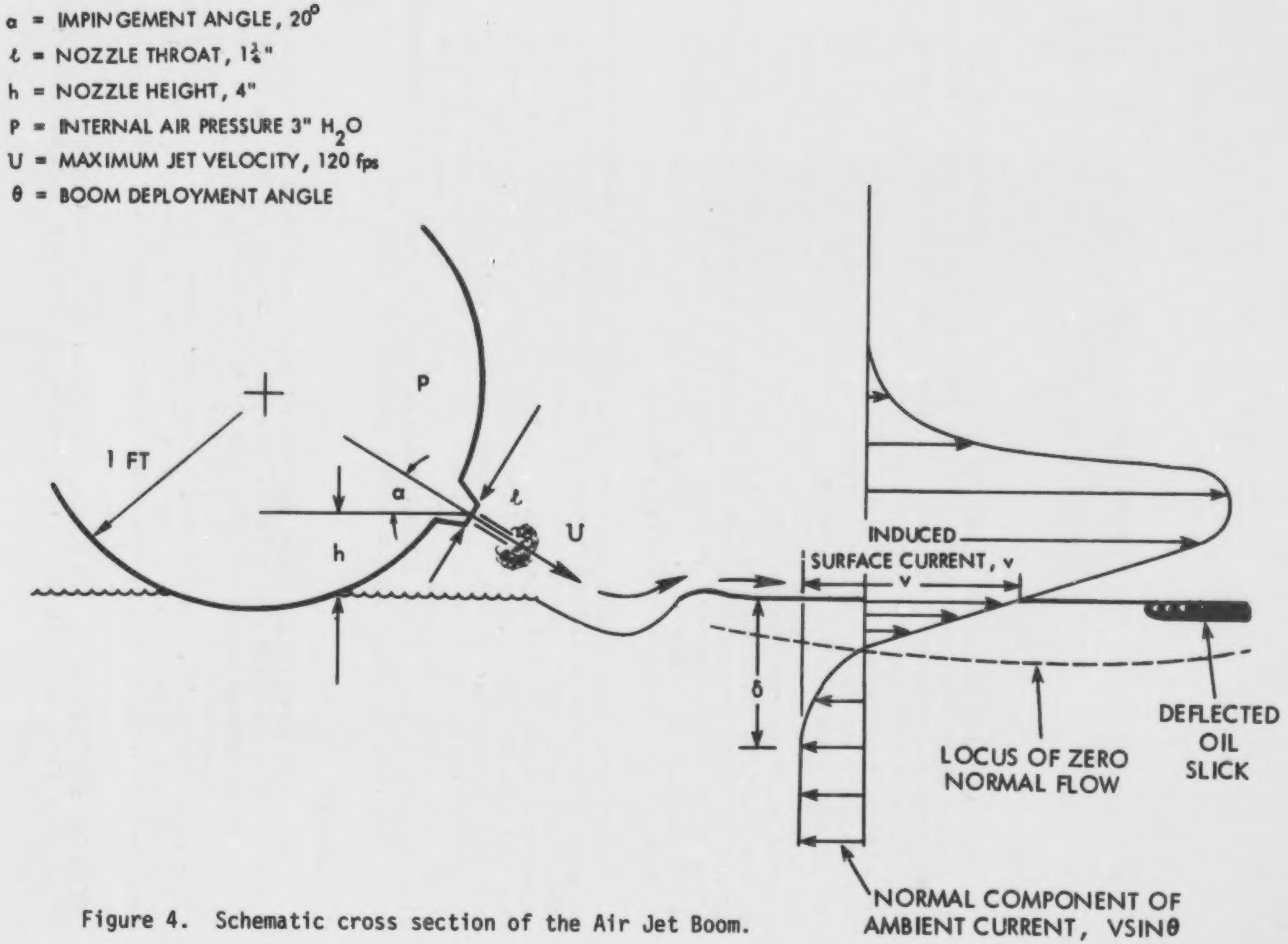
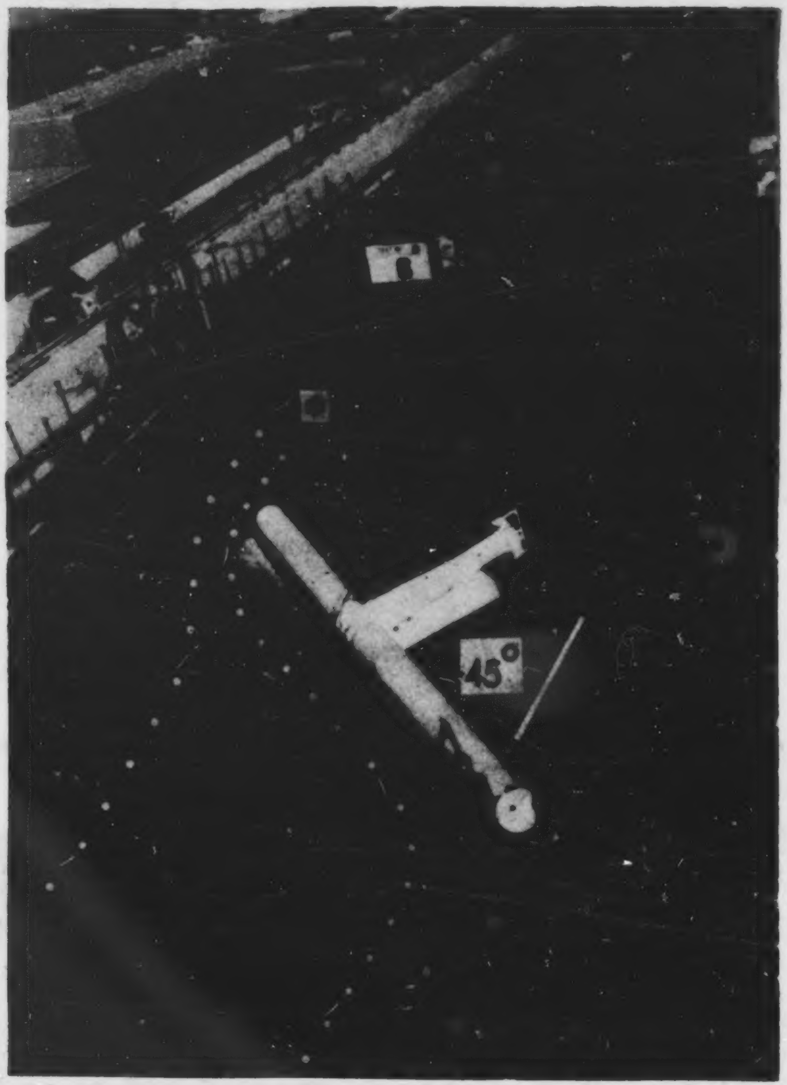

α = IMPINGEMENT ANGLE, 20°
ℓ = NOZZLE THROAT, $1\frac{1}{4}$"
h = NOZZLE HEIGHT, 4"
P = INTERNAL AIR PRESSURE 3" H_2O
U = MAXIMUM JET VELOCITY, 120 fps
θ = BOOM DEPLOYMENT ANGLE
1 FT
P
α
h
ℓ
U
INDUCED SURFACE CURRENT, v
v
δ
LOCUS OF ZERO NORMAL FLOW
DEFLECTED OIL SLICK
NORMAL COMPONENT OF AMBIENT CURRENT, VSINθ

Figure 4. Schematic cross section of the Air Jet Boom.



* Typical trajectories of oil slick particles

FIGURE 5. Calm water test at OHMSETT (1.5 knot current, $\theta = 45^\circ$).

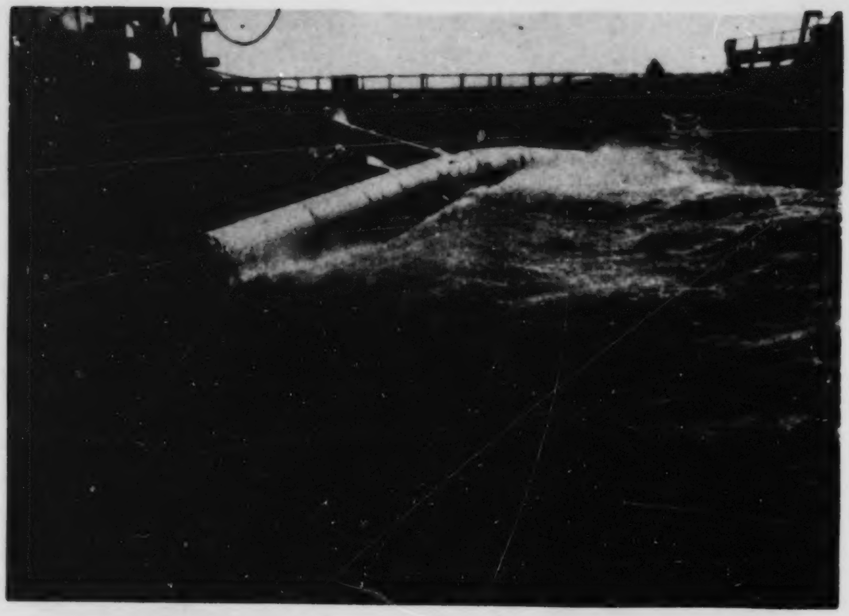


Figure 6a. Wave conformance (OHMSETT).

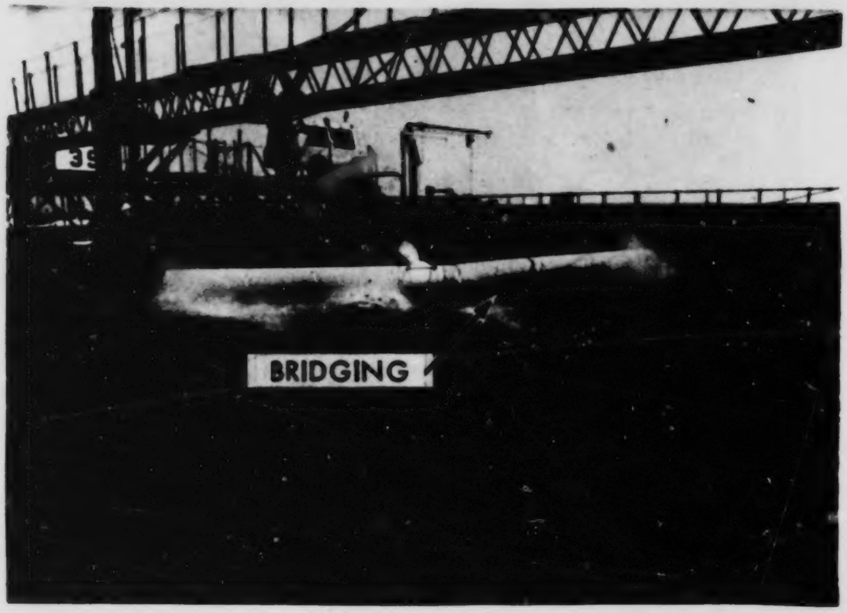

39
BRIDGING

Figure 6b. Bridging between waves (OHMSETT).

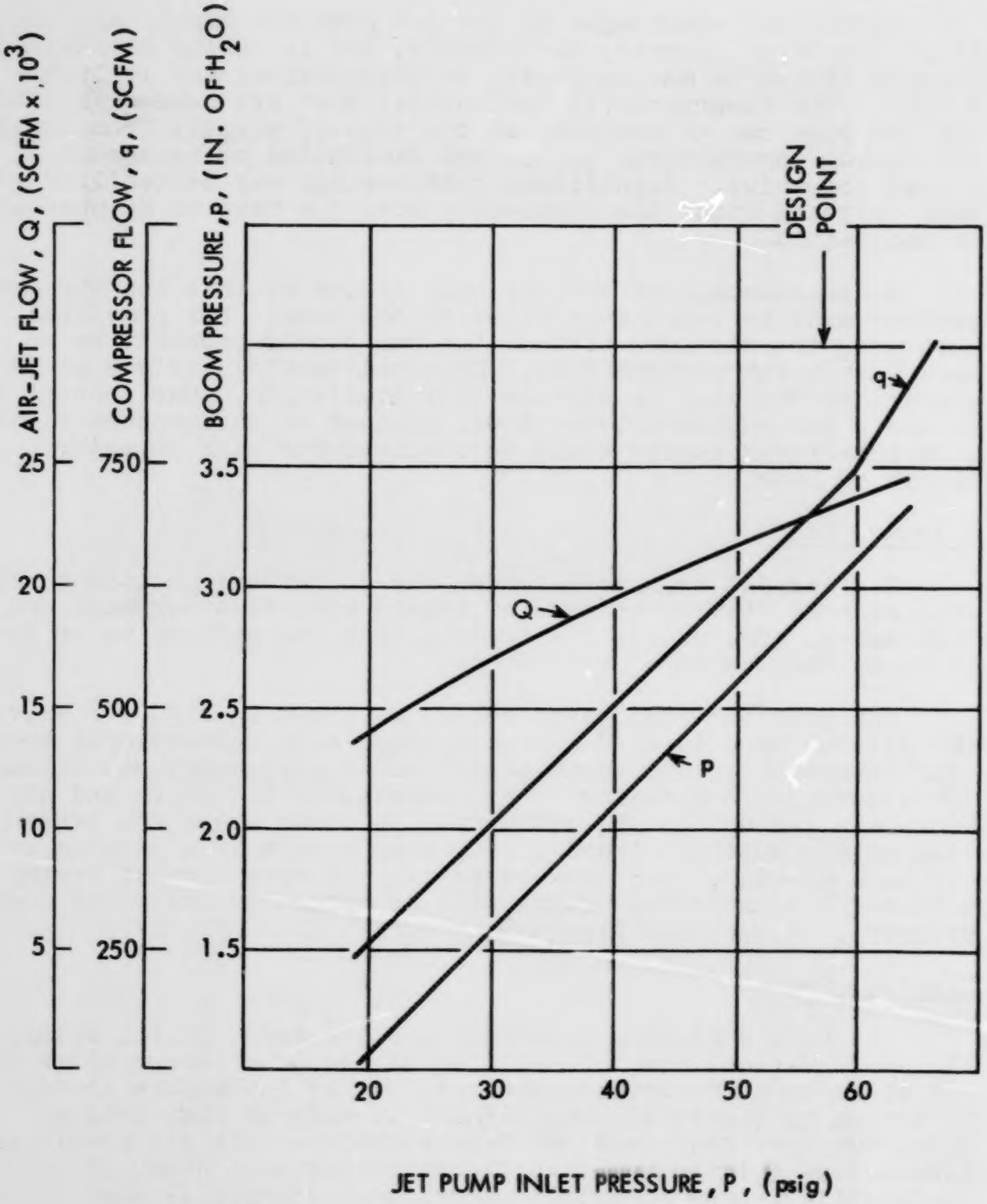


Figure 7. Jet pump performance (Summary of test results).

Particular advantages of the jet pump air supply are that it is simple to operate, is reliable, and is easily maintained because it has no moving parts; is inexpensive; and is lightweight. The compressor(s) and hose(s) that are needed to drive the jet pump can be procured at the time of a spill from local industrial contractors, government facilities or equipment rental companies. Significant cost savings may be realized with this approach since the compressor does not have to be purchased or maintained.

A disadvantage of the jet pump system is that the air compressor must be reasonably close to the boom. For practical purposes, the distance between the two should probably be no more than a few hundred feet. Other air-moving systems could be adapted to the boom to obviate this limitation. One concept is to use a gas-engine driven blower mounted on the support float; a 28 horsepower engine would be required for each 10-meter length of boom.

Intended Use

The Air-Jet Boom is intended for deployment on inland waterways such as rivers, streams or inlets with fast currents and/or high waves. The boom's low draft allows the minimum water depth to be as shallow as 4 or 5 inches.

One possible deployment scheme is shown in Figure 8 where the Air-Jet Boom is used in conjunction with conventional booms (for diversion in quiescent areas) and a stationary oil skimmer for recovery. Compressor(s) are located on the shore and air hoses are led out to the jet pump. In cases where the extension of air hoses is impractical, road access is a problem or air-hose pressure drops are excessive. A more complex deployment could be achieved using boats or barges to carry the compressors, as shown in Figure 9.

Rigging

The boom's rigging transfers applied loads (i.e., mainly the support-float drag) to mooring cables or adjacent booms without disrupting the wave conformance of the inflatable section. Referring to Figure 10, the rigging is made of five cables: one main, two rear stays and two radius cables. All are prefit and attached by quick connecting/disconnecting snap hooks (Figures 11a and 11b). One important operational feature is that if the inflatable sections buckle (see Figure 10, position 2) from high impact loads or passing debris, the radius cable will slide along the main cable to alleviate stress which otherwise might tear up or pull off the inflatable section. Air pressure restores the shape when the load is released.

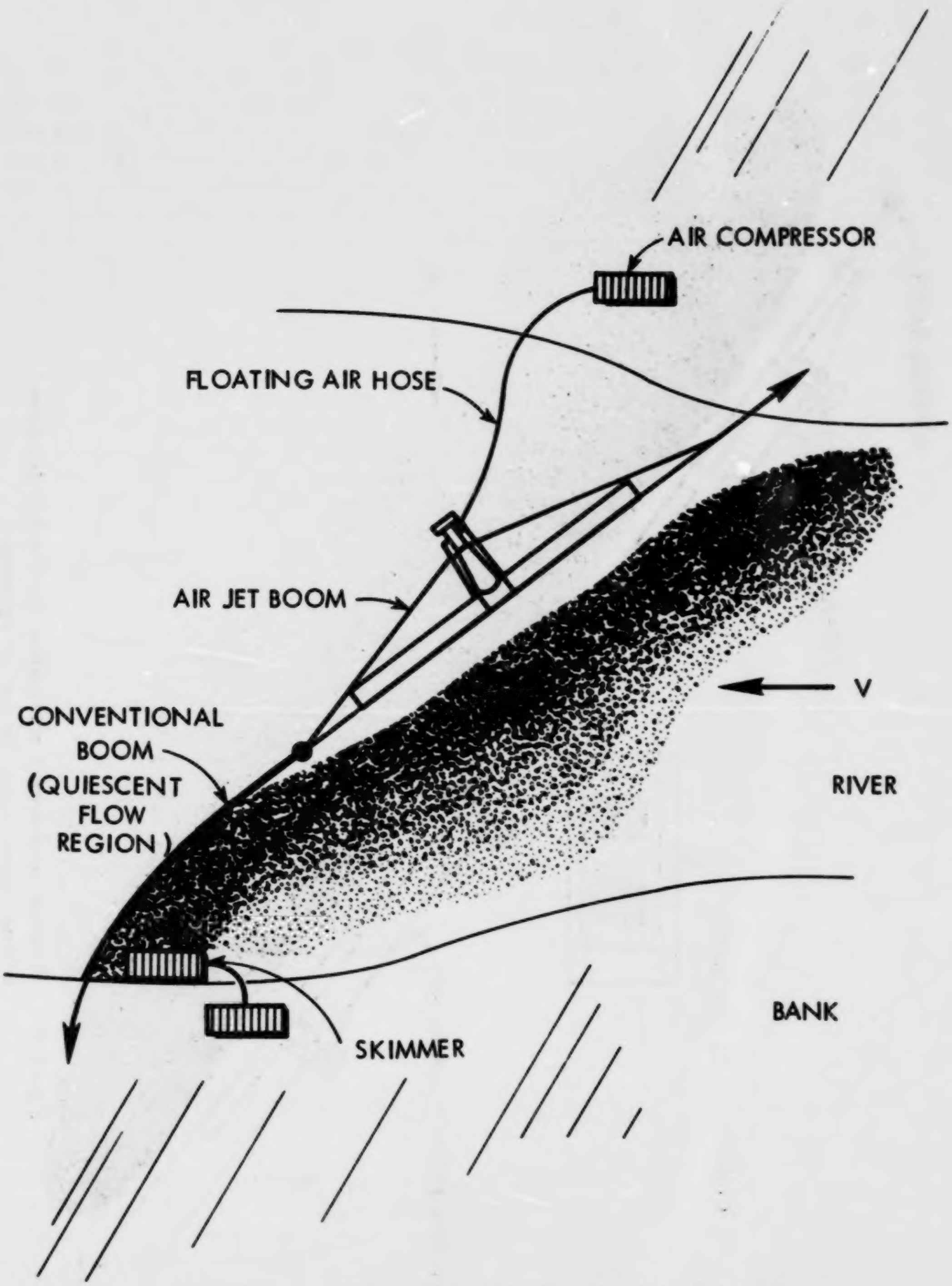

AIR COMPRESSOR
FLOATING AIR HOSE
AIR JET BOOM
V
CONVENTIONAL BOOM (QUIESCENT FLOW REGION)
RIVER
BANK
SKIMMER

Figure 8. Proposed deployment of the Air Jet Boom.

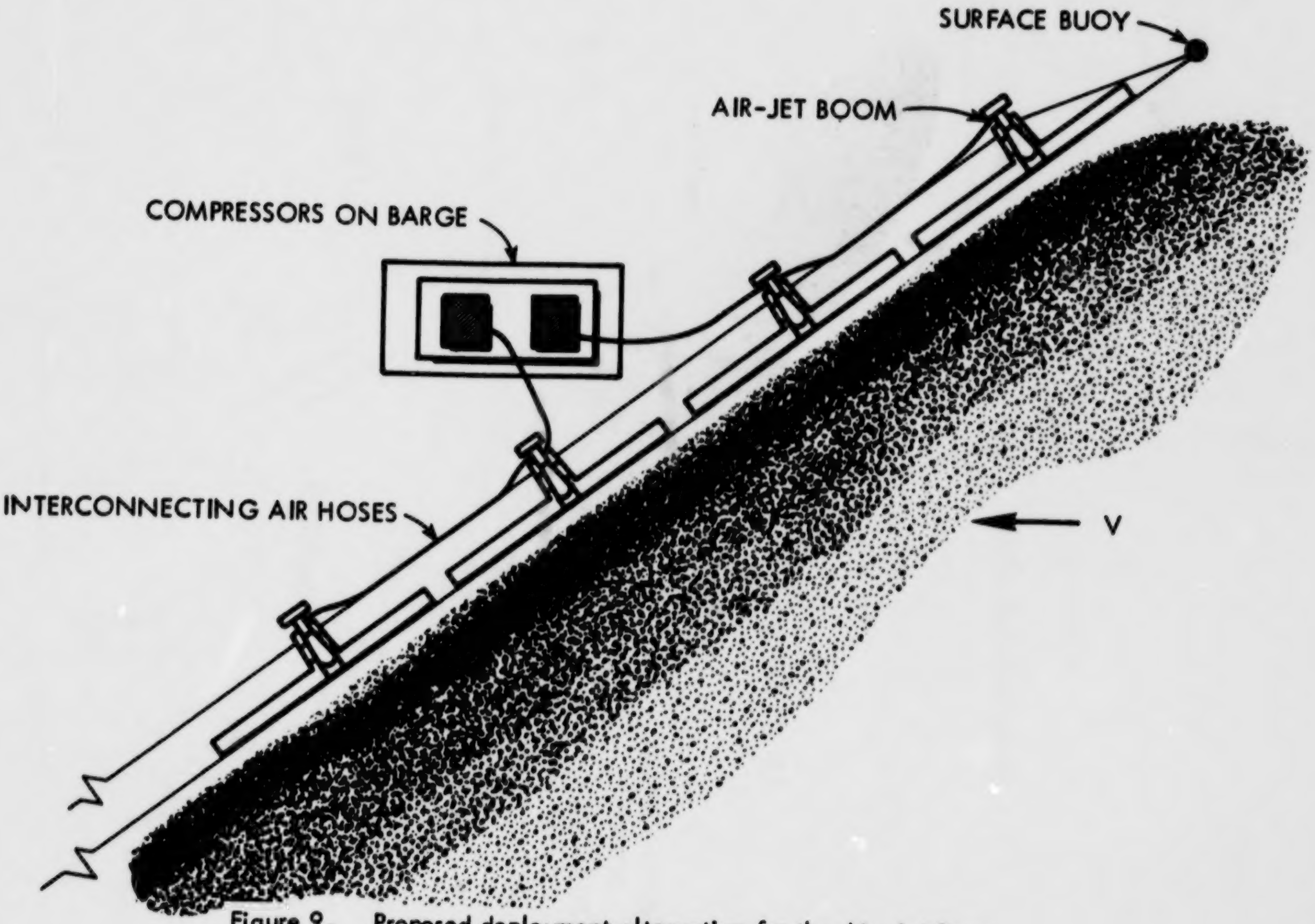

SURFACE BUOY
AIR-JET BOOM
COMPRESSORS ON BARGE
INTERCONNECTING AIR HOSES
V

Figure 9. Proposed deployment alternative for the Air-Jet Boom without shore access for the air compressor

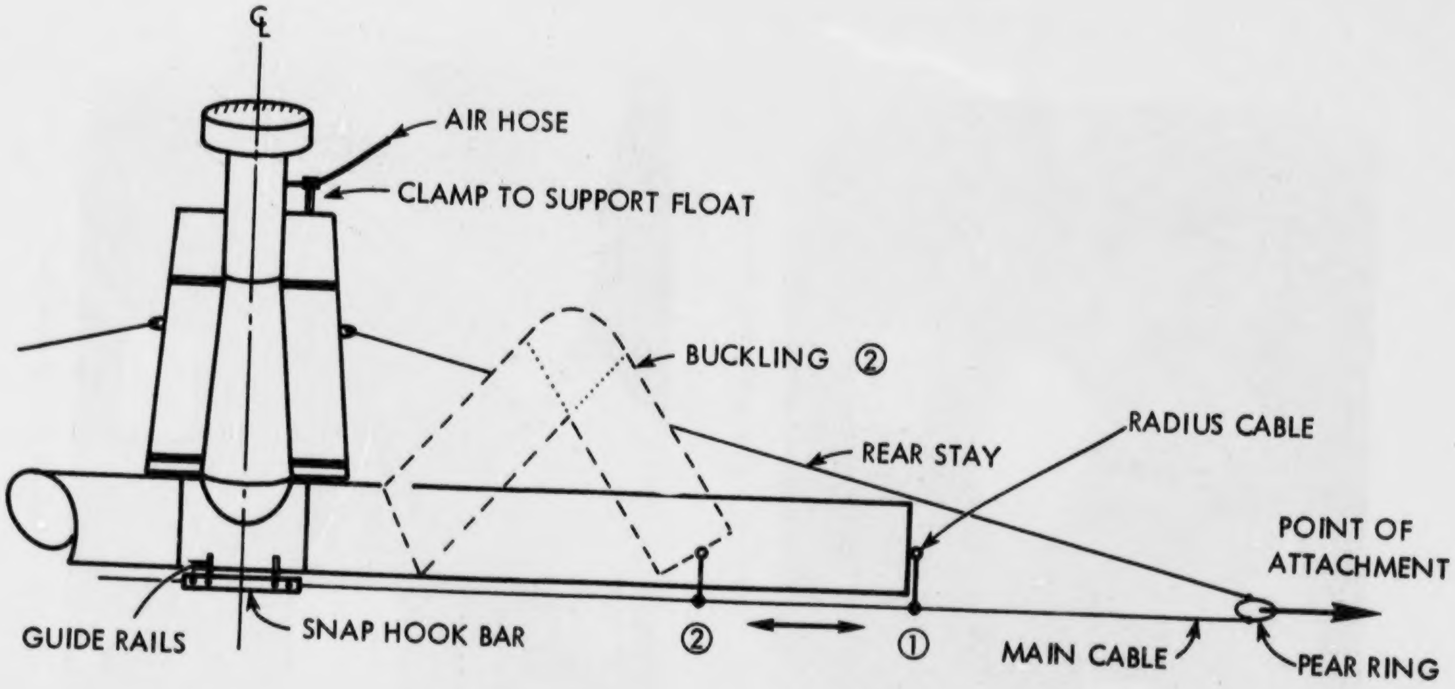

℄
AIR HOSE
CLAMP TO SUPPORT FLOAT
BUCKLING ②
RADIUS CABLE
REAR STAY
POINT OF ATTACHMENT
GUIDE RAILS
SNAP HOOK BAR
②
①
MAIN CABLE
PEAR RING

Figure 10. Rigging for the Air-Jet Boom.

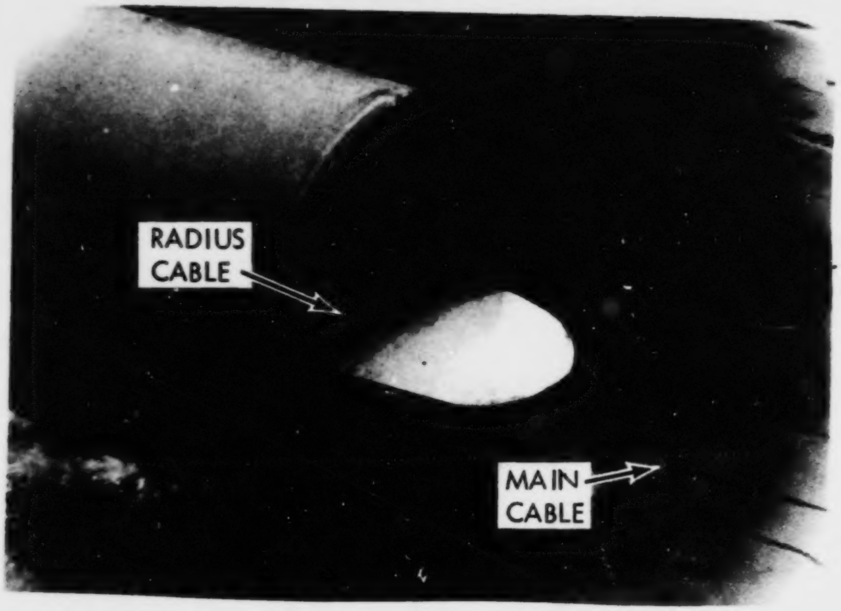

RADIUS
CABLE
MAIN
CABLE

Figure 11a. Detail of radius cable and fairing.

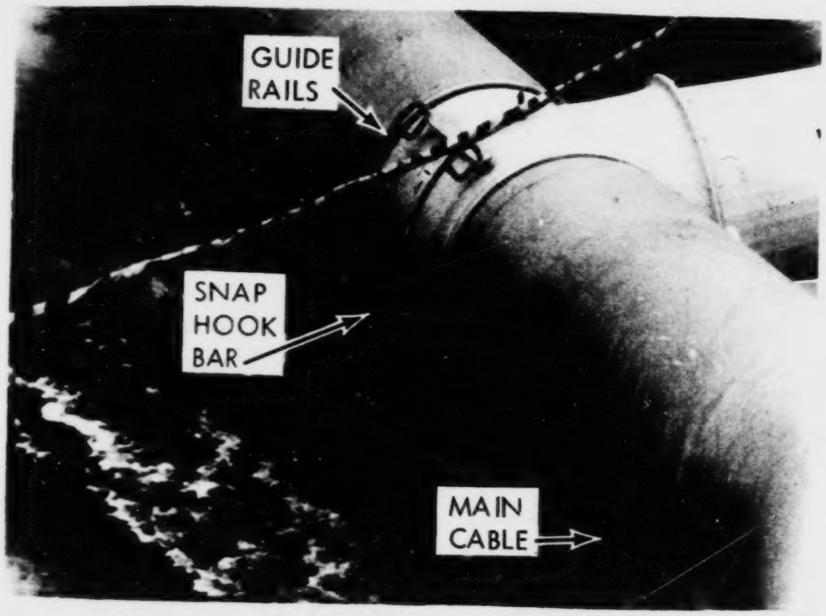

GUIDE
RAILS
SNAP
HOOK
BAR
MAIN
CABLE

Figure 11b. Detail of snap hook bar.

A rigging concept for two or more booms is proposed as shown in Figure 12.

Deployment

The deployment of the Air-Jet Boom is in some ways similar to that of conventional booms. The deployment suggested in Figure 8 could be accomplished as follows:

1. Set the main cable between any two points; for example, between conventional booms and the shore or between a skimmer and a surface buoy. Ideally, the cable should be about 1 foot above the water surface.
2. Tow the boom, with the inflatable sections folded on top of the jet pump, to the center of the cable and attach the snap hook bar (on the main cable) to the guide rails on the center section of the boom.
3. Clip on the rear stays between the pear rings at each end of the main cable to the respective attachment rings on the support float*.
4. Tow the compressor hose out to the support float. Idle the compressor to keep water out of the hose. (Note: Standard commercial 2-inch ID hose will float even when partially filled. Water in the hose will not damage the boom.) Make the air hose connection to the support float; a hand-tight connection is sufficient. An alternative would be to connect the hose on shore and tow both the hose and the support float to the main cable together.
5. Signal to shore to increase the compressor speed; the inflatable sections will begin to unfold with increased compressor output. With the sections fully or partially inflated, clip the radius cables to the main cable. Any water located in the boom will be automatically purged through ports in the end plates to complete the deployment.

Storage

The inflatable sections, when deflated, can be folded into a small, lightweight package about 8 inch by 8 inch by 40 inch, weighing less than 20 pounds. These sections can then be nested

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*If two or more booms are deployed, the rear stays are connected to adjacent support floats, whereas the rear stays for the outermost boom are connected to the pear rings as shown in Figure 10.

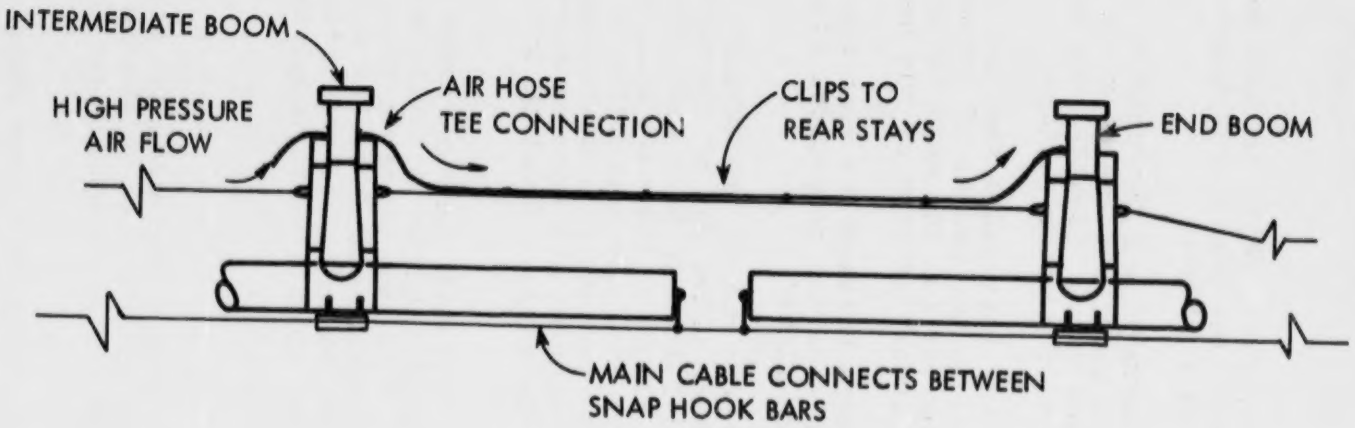

INTERMEDIATE BOOM
HIGH PRESSURE AIR FLOW
AIR HOSE TEE CONNECTION
CLIPS TO REAR STAYS
END BOOM
MAIN CABLE CONNECTS BETWEEN SNAP HOOK BARS

Figure 12. Rigging for multiple Air Jet Boom deployment.

into the area between the jet pump and support float. Overall dimensions of the stored unit are approximately 4 feet by 10½ feet by 3½ feet high; it weighs a total of 380 pounds**.

**Because of the steel/wood/Fiberglas construction, the weight of the prototype is overly high. A production-type version would be considerably lighter; possibly 150 pounds.

SECTION 5

DEVELOPMENT PROGRAM SUMMARY

The Air-Jet Boom concept was developed in four successive tasks:

1. Design and Fabrication
2. OHMSETT Proof Test
3. Modification
4. OHMSETT Performance Tests

A brief overview of each task is given below, while details are relegated to later sections of this report.

DESIGN AND FABRICATION

Based on EPA design guidelines, a prototype version of the Air-Jet Boom was designed and fabricated. Section 6 describes the technical approach, important design criteria and procedures used for the design of the boom, including the inflatable sections, jet pump and support float.

OHMSETT PROOF TESTS

Proof tests to evaluate the performance of the Air-Jet Boom prototype in waves and currents that might be encountered in a real spill were conducted under controlled reproducible conditions of the EPA's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT). Test objectives were to determine the intrinsic operational limitations of the air-jet concept, and to discover whether there were any structural limitations imposed by the design. One conclusion of these tests (described in detail in Section 7) was that when the angle between the boom axis and flow is 30 degrees, complete oil diversion was generally limited to currents below about 2.5 knots, whereas structural failures (i.e., folding of one boom leg) occurred between 4 and 5 knots.

MODIFICATION

The objective of this task was to rectify the problems that were disclosed by the Proof Tests. Clearly, a primary goal was to improve the boom's diversion performance in currents greater than 2½ knots. Section 8 describes the general method of approach and a description of the modifications that were subsequently made to the prototype boom.

OHMSETT PERFORMANCE TESTS

Using the modified version of the Air-Jet Boom, tests were conducted at OHMSETT that were similar to the earlier Proof Tests; however, greater emphasis was placed on delineating the performance limits over a wider range of operating conditions, including smaller boom deployment (diversion) angles and reducing compressed air supply. The test results, described in Section 9, show that the limiting current for complete diversion was increased (from 2½ knots) to 3 knots. At the reduced deployment angle (20 degrees), diversion could be achieved at speeds up to 4 knots.

SECTION 6

DESIGN AND FABRICATION

The design of the Air-Jet Boom was based, at least in a general way, on guidelines provided by the Environmental Protection Agency. These guidelines are included in Appendix B.

The following paragraphs describe the approach and methodology leading to the overall boom design and the designs for the three principal components: the inflatable fabric sections, the jet pump and its support float. In many areas, the final design evolved after several sequential steps.

INFLATABLE SECTIONS

Functional Requirements

The inflatable section serves both as a duct to distribute the air flow and as a foundation to support the air-jet nozzle. Specifically, the section must have appropriate structural characteristics and ruggedness to withstand internally and externally applied loads and to maintain the continuity and orientation of the air jet both in calm water and in waves. In addition, it should be compactable, and easy to fabricate, clean and maintain.

Structural Analysis

The inflatable section is a fabric cylinder supported by internal air pressure and attached at one end to the boom's center "T" section. Considering ways in which this section can fail, two types of failure may be defined:

- Structural Failure - a tearing or bursting of the fabric.
- Structural Instability - a severe distortion of the cylindrical formation without structural failure.

Designing to prevent the first of the two types of failure was straightforward since it amounted to selecting an appropriate fabric. The problem was further simplified because the level of stress in this application was well below the strength of most off-the-shelf fabrics used in the fabrication of oil booms. Appendix C describes the fabric selection criteria, properties of the selected fabric and some brief tests concerning joint efficiency (heat sealing) and rate of creep under steady load.

The second of the two failures, structural instability, is especially important with respect to the performance of the boom; large distortions will disrupt the continuity and/or orientation of the air jet. Consequently, an analysis (described in Appendix D) was undertaken to anticipate the structural characteristics of the inflated section and to disclose what type of additional support (e.g., cables), if any, would best prevent structural instabilities. Two general modes of instability were considered:

- Lateral Instability - causing the inflatable sections to buckle or fold under the action of applied lateral loads.
- Torsional Instability - causing the inflatable sections to rotate away from the proper air-jet angle under the action of applied moments.

The analysis indicated that the inflatable sections require additional support (i.e., in addition to the cantilever-type attachment to the "T" section) to prevent lateral instability (see Appendix D, Case 1), and that a simple end support will be sufficient to prevent this instability (see Appendix D, Case 2). Moreover, we found that no additional support (e.g., an internal helical spring) would be required to prevent torsional instability (Appendix D, Case 3).

Wave Conformance

Wave conformance (i.e., deflection and/or buckling of the inflatable section in the vertical direction) allows the air jet to remain within reasonable proximity to the free surface. Appendix D considers the ability of the section to conform under two wave conditions. One condition concerns waves with lengths greater than the projected length of the section ($\lambda > \ell_1 \cos \theta$) and, the other pertains to waves with lengths equal to or less than the projected length of the section ($\lambda \leq \ell_1 \cos \theta$). The results indicated that conformance will probably not be a problem in the first case, while in the latter case (i.e., $\lambda \leq \ell_1 \cos \theta$), "bridging" could occur between adjacent wave creses (see Figure 6).

Resonant Interactions

Calculations of the inflatable section's natural frequencies in lateral and torsional modes for the undamped case (Appendix D) demonstrated that resonant interactions will probably not occur because the natural frequencies are high and there will be significant damping of motions from interactions with the free surface.

Nozzle Design

The air-jet nozzle is intended to provide a coherent air jet directed at the desired impingement angle to the free surface. Besides achieving this in calm water, the nozzle must be sufficiently flexible to bend with the inflatable sections, yet maintain the air-jet coherence and orientation in waves. Additionally, the nozzle must be compactable for storage and easy to fabricate.

Several designs were evaluated, including folding rigid nozzles, inserts into formed fabric sleeves, sewed or glued on nozzles and all-fabric nozzles. Two concepts using all-fabric construction were considered to be most suitable because of their flexibility and continuity of the air-jet and ease of construction. Preliminary models of these configurations are shown in Figure 13.

Tests were conducted with these models to compare the coherence and maximum velocities of the air jet for 3/4-inch throat at 3.25 inches of water pressure (see Appendix B, item 7). The results given in Figure 14 indicate that the "external" design was preferable over the "internal" one. Moreover, the external nozzle is judged to be superior from a structural standpoint because it is more capable of transferring the membrane stress across the nozzle gap without distorting the nozzle shape. Hence, further tests of the external fabric nozzle concept were conducted using a variable geometry assembly to determine the optimum nozzle convergence angle. Here, a 25-degree double angle was found to be best,although the variations in conformance were not significant in a range from 15 to 60 degrees.

A mockup of the prototype section (see Figure 15a) was built with selected fabric to demonstrate the feasibility of construction, and was tested to confirm the aerodynamic performance of the fabric nozzle. These tests, in conjunction with dead load tests (see Figure 15b), showed the nozzle to be generally satisfactory, although some refinements in the construction technique were required. For instance, heat-sealed construction was abandoned in favor of a sewed construction (shown in Appendix A). With sewed construction, a major advantage is direct attachment between the substrates; this prevents delamination of the coating and distortion of the nozzle shape, which was experienced with the heat-sealed joints.

End Plate and Clamping Arrangement

The end plate closes off the inflatable section and provides a point of attachment for the radius cable connection described previously (see Figures 10 and 11a). The end plate is a fabric-covered plywood disc. It is attached to the fabric cylinder by means of a clamp, much like a hose clamp, encased in a vinyl tube

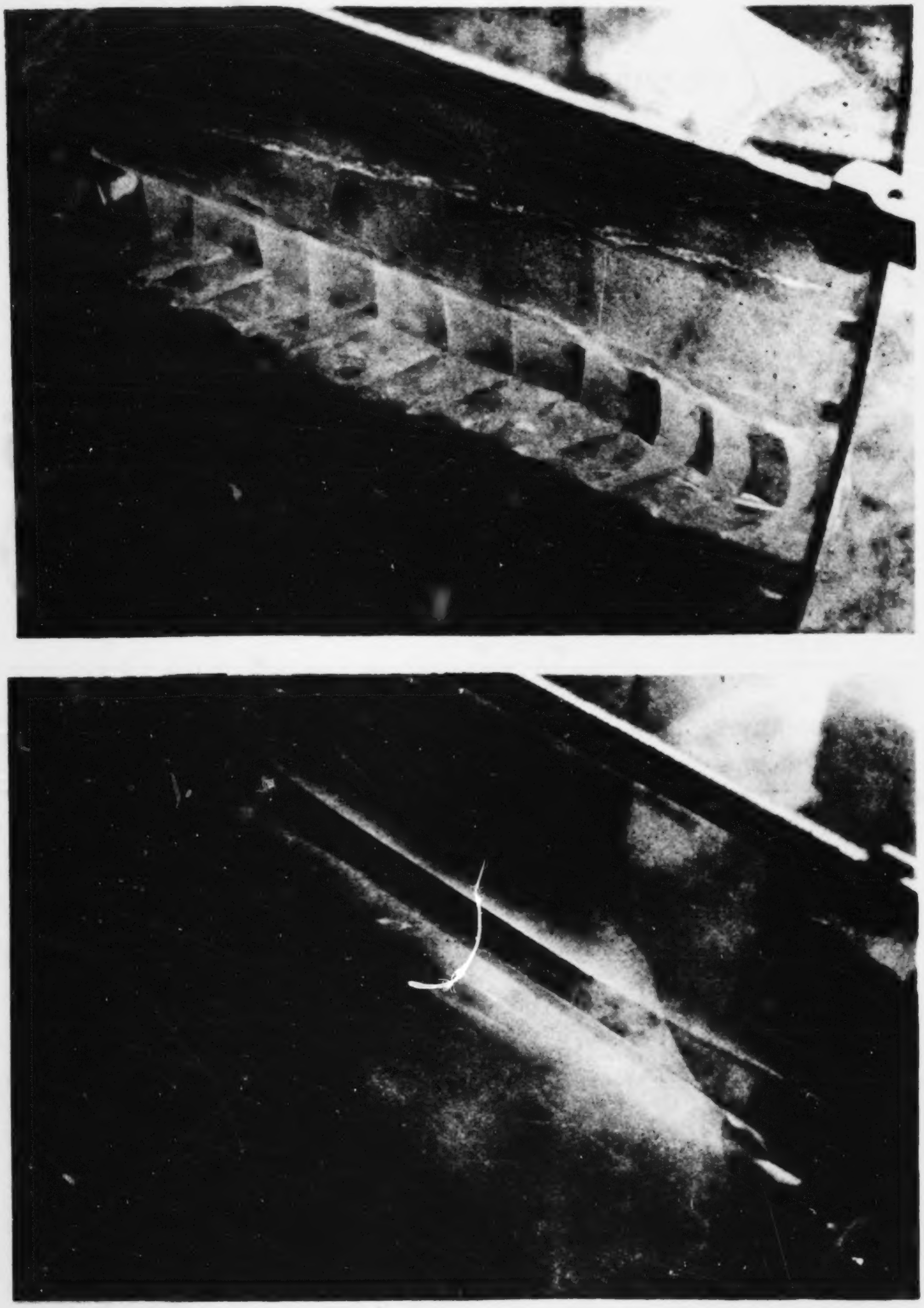
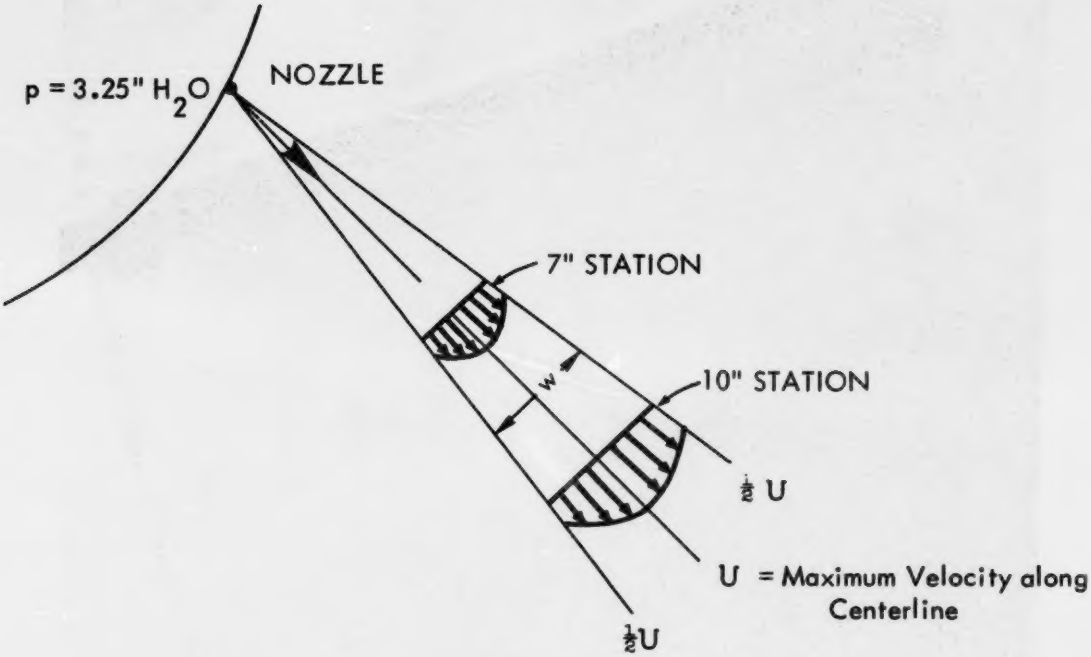


Figure 13 - Models of preliminary nozzle configurations at specified operating conditions (view from inside boom).


$p = 3.25" H_2O$
NOZZLE
7" STATION
w
10" STATION
½ U
U = Maximum Velocity along Centerline
½U

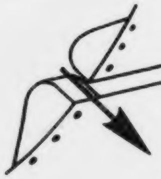
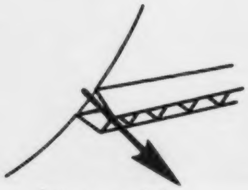
PRELIMINARY DESIGN	MAXIMUM VELOCITY / JET WIDTH		
	AT NOZZLE	AT 7 INCH STATION	AT 10 INCH STATION
 (Internal)	115 fps	76 fps w = 2 inch	53 fps w = 3 inch
 (External)	116 fps	92 fps w = 1 inch	72 fps w = 2 inch

Figure 14. Velocity profiles for preliminary nozzle configurations.

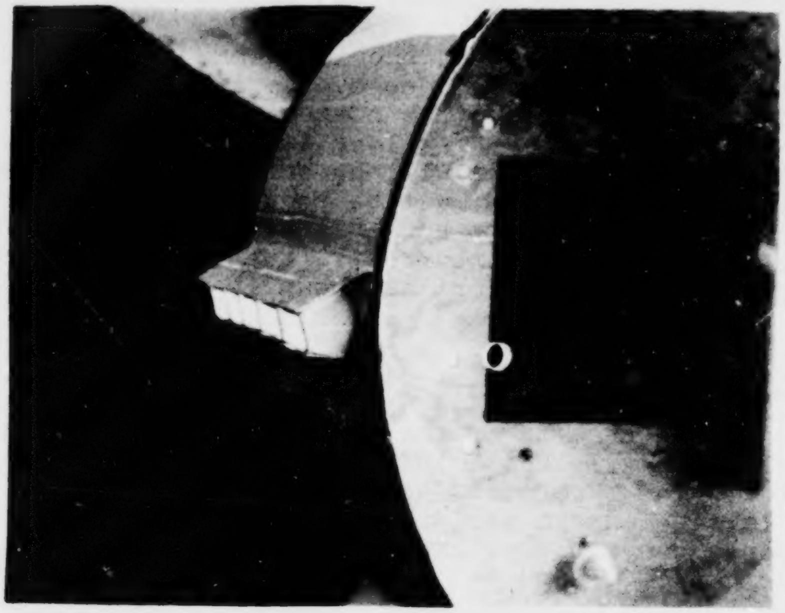


Figure 15a. Nozzle structural and aerodynamic test .

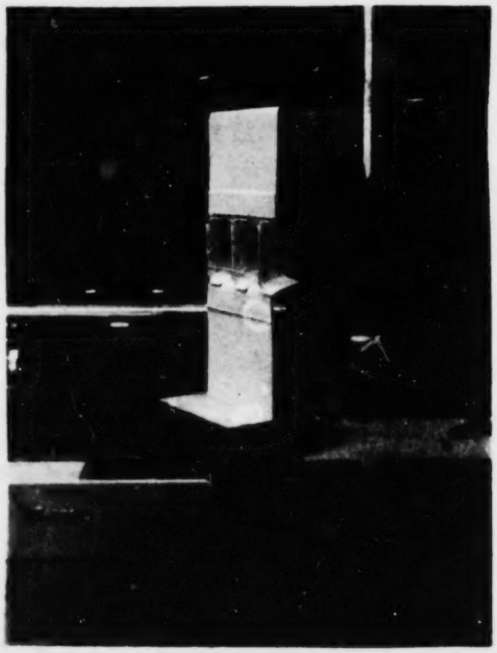


Figure 15b. Nozzle dead load tests.

to prevent cutting or abrasion of the fabric.

If the inflatable section should become filled with water (e.g., when the boom is being deployed), it will blow out of a small port located at the bottom of the end plate. Air normally bubbles out of the opening. As long as there is some air pressure in the boom, most water will be bailed out; however, to remove all water the pressure must be equal to at least 1 inch of water (i.e., the approximate boom draft). To prevent water from reentering the port in high currents (due to dynamic head), a cowl is provided over the port as shown in Figure A-3 (Appendix A).

Full Length Prototype

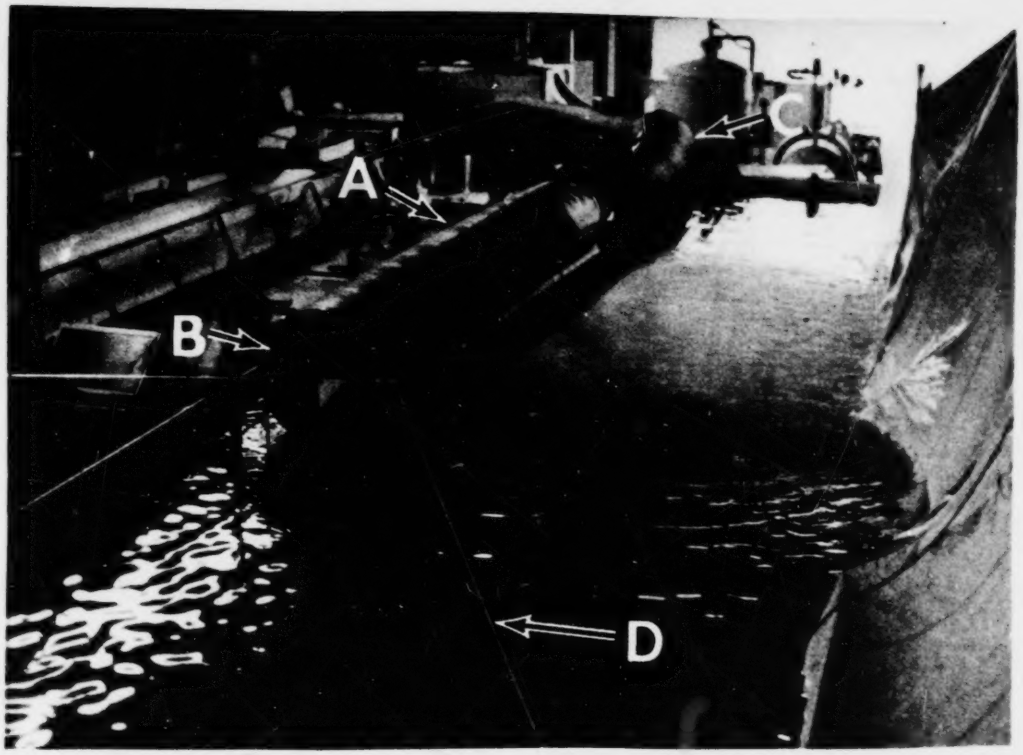
Based on the results of the structural analysis and the nozzle design, a full-length inflatable section was built and demonstrated. The laboratory setup for the demonstration, shown in Figure 16, included a variable output blower with flexible duct to supply the air flow and a clear plexiglass and plate to permit observation inside the section.

The objectives of this phase in the development were to check the cylinder's stability in bending and torsion, and any tendency for vibrations or oscillations in the nonreinforced structure, and to make sure of the orientation and uniformity of the air jet along the length of the section. Evaluations were conducted at design pressure (3.25 inches of water) and off-design conditions (2.65 and 3.85 inches of water). In all, the inflatable section performed as anticipated. Velocity and pressure surveys revealed that the air jet was uniform along the length of the boom. Vertical measurements between the nozzle and free surface indicated minor twisting along the length of the boom. Moreover, with a total of 18 hours operating time, the fabric nozzle demonstrated excellent dimensional stability.

JET PUMP

Functional Requirements

The jet pump provides the low-pressure, high-volume flow that is required to supply the air jet. It consists of an array of nine high-pressure nozzles, a constant area mixing chamber, and a diffuser section as shown in Figure 17. The nozzles are fed high-pressure air (~ 750 SCFM @ 58 psi) from a (shore-based) air compressor. The nozzles discharge high-velocity jets into the mixing chamber that entrain surrounding ambient air into the bellmouth. The ambient and high-pressure air is combined into a moderage velocity, low-pressure flow in the mixing section. The diffuser then expands the flow, reducing the velocity and increasing the pressure to the level that is required by the in-



A	INFLATABLE SECTION PROTOTYPE
B	END PLATE
C	SUPPLY AIR DUCT
D	TEMPORARY SUPPORT CABLE

Figure 16. Laboratory demonstration of prototype inflatable section in still water.

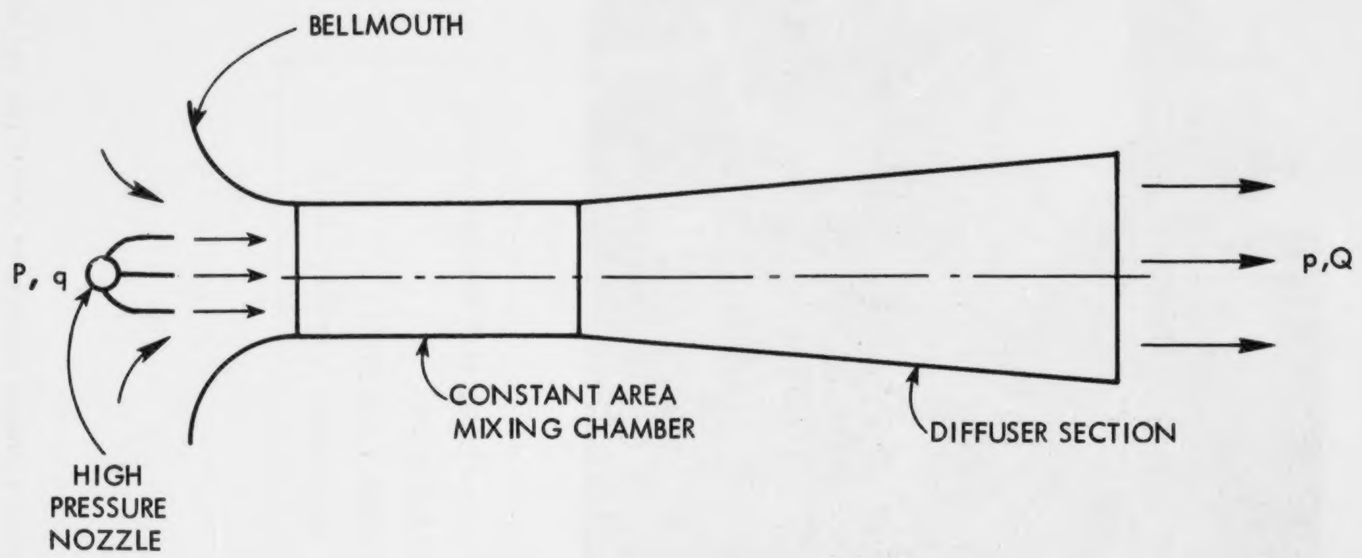

BELLMOUTH
P, q
p,Q
CONSTANT AREA
MIXING CHAMBER
DIFFUSER SECTION
HIGH
PRESSURE
NOZZLE

Figure 17. Schematic of the jet pump.

flatable sections. Note that there are no moving parts in the jet pump.

Design

The design of the jet is based on well-known principles (see Reference 5). The design point and some parametric relationships are shown in Figure 18. Details of the jet pump design, including the downstream tee section and turning vane arrangement (to supply two inflatable legs), may be found in Appendix A.

Performance Tests

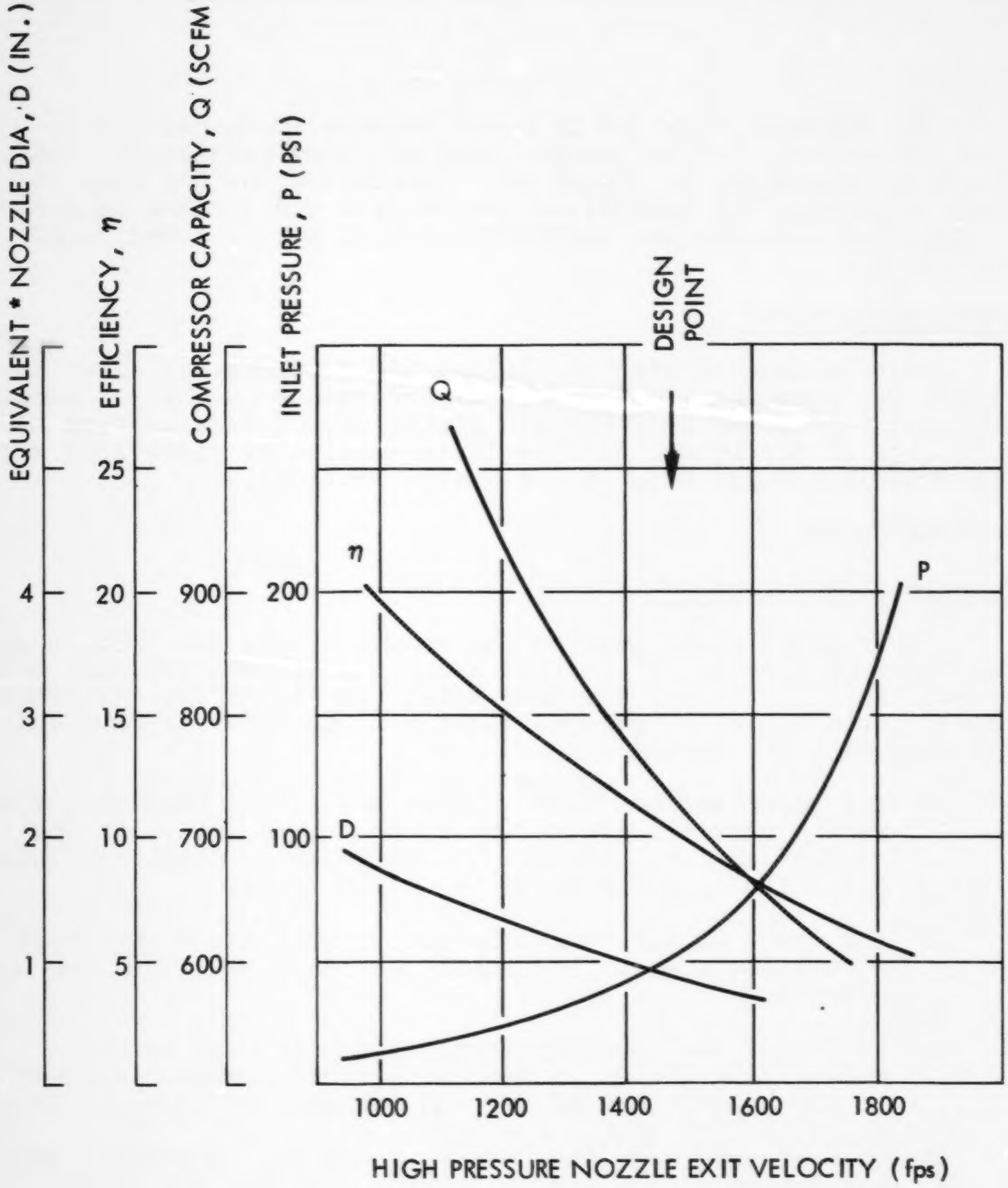
Tests conducted with two inflatable sections, as shown in Figure 19, confirmed the predicted performance of the jet pump. Measured velocities and pressure distributions were uniform along both legs of the boom. No flow instabilities or vibrations were observed in the jet pump or inflatable sections.

SUPPORT FLOAT

Functional Requirements

The support float carries the weight of the jet pump, turning vanes and center "T" section and, in addition, provides rotational stability (about the boom axis) for the inflatable sections. We set forth a list of general factors to consider in developing the support float design:

- The support float must support the entire boom when the fabric sections are deflated and folded on top of the center section. It must be sufficiently stable in this condition to allow it to be easily towed.
- The draft of the center T-section must match the draft of the (dewatered) inflatable sections when they are extended.
- It should remain sufficiently level in high currents and varying angles of attack to prevent marked changes in the orientation of the air jet with the free surface.
- It must have adequate reserve buoyancy, waterplane area and dynamic stability to survive expected sea states while maintaining the draft of the center T-section.
- It should be light in weight to insure low drag and ease of deployment, yet strong enough to withstand applied loads and rough handling.



* NOTE: THE TOTAL NOZZLE AREA IS DISTRIBUTED BETWEEN NINE NOZZLES IN
THE PRESENT DESIGN

Figure 18. Theoretical jet pump characteristics.

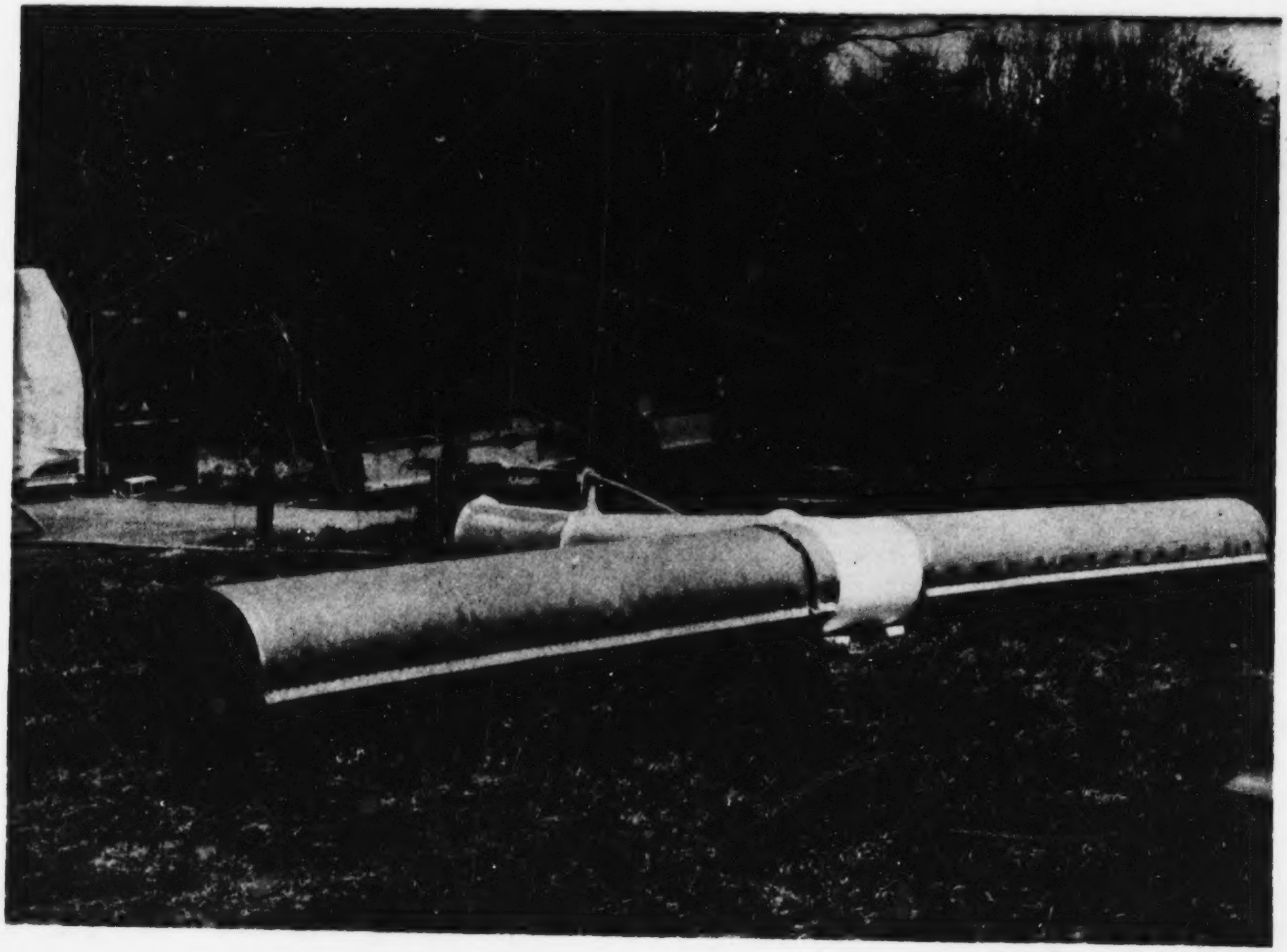


Figure 19. Jet pump performance tests (results are shown in Figure 7).

Design and Assembly

Based on the above guidelines, a catamaran-type hull was initially selected because of its characteristically good stability when the boom is deflated. The extended hull length contributes to rotational stability to maintain the desired air-jet orientation.

Construction was a composite of light-gauge sheet metal filled with expandable urethane foam to prevent loss of buoyancy. Plywood supporting structure was used to connect the hull to the jet pump*. A key step in the assembly procedure was to set the jet pump and center T-section on the hulls in still water using a temporary wooden cradle. The cradle was then cut away as required to adjust the T-section draft to match the draft of the inflatable section (about one inch) while maintaining the support float at zero trim and heel angles. The temporary cradle was then used as templates to cut the permanent plywood support structure.

Towing Tests

After this assembly was completed, still water tests (in the flume shown in Figure 16) were conducted to find the float's longitudinal center of resistance. Rigging eyes were then attached as appropriate. Brief towing tests were then conducted in the HYDRONAUTICS Ship Model Basin (HSMB®) as shown in Figure 20. From these tests we found that additional flotation was required at the aft end of the float. A bottom plate joining the two hulls was also added. Even with these improvements, the float's stability was marginal in a 5-knot current at an angle of 45 degrees.

Returning the jet pump/support float to still water, the nozzle on center T-section was located with respect to the free surface. This final alignment was important because the rigid nozzle is the "witness mark" for setting the inflatable sections on the center T-section.

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*The method of construction was chosen so that modifications could be made with minimal difficulty.

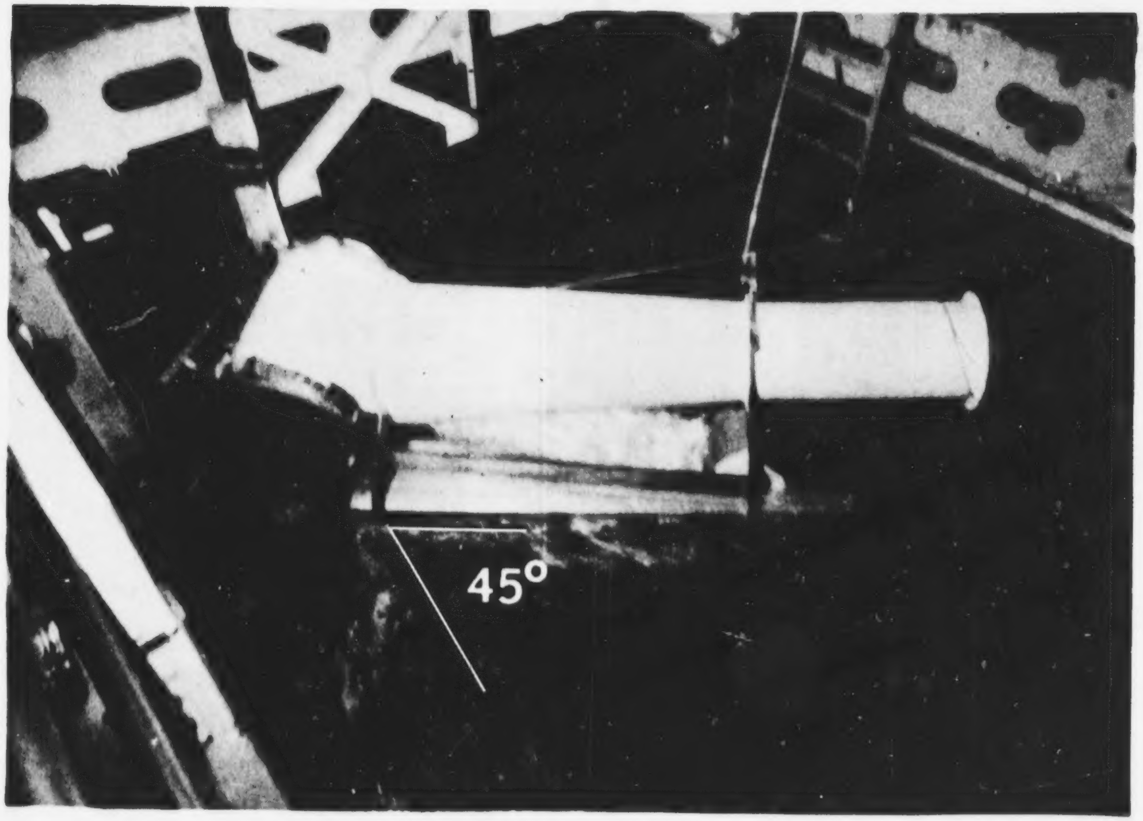


Figure 20. Support float towing towing tests - Hydronautics Ship Model Basin (HSMB ®).

SECTION 7

OHMSETT PROOF TESTS

GENERAL OBJECTIVES

Proof tests were conducted at the Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) to evaluate the performance characteristics of the Air-Jet Boom under environmental conditions which might be encountered in an actual oil spill. The conditions were varied systematically to determine how the performance of the boom is affected by current, waves and boom deployment angle, etc.

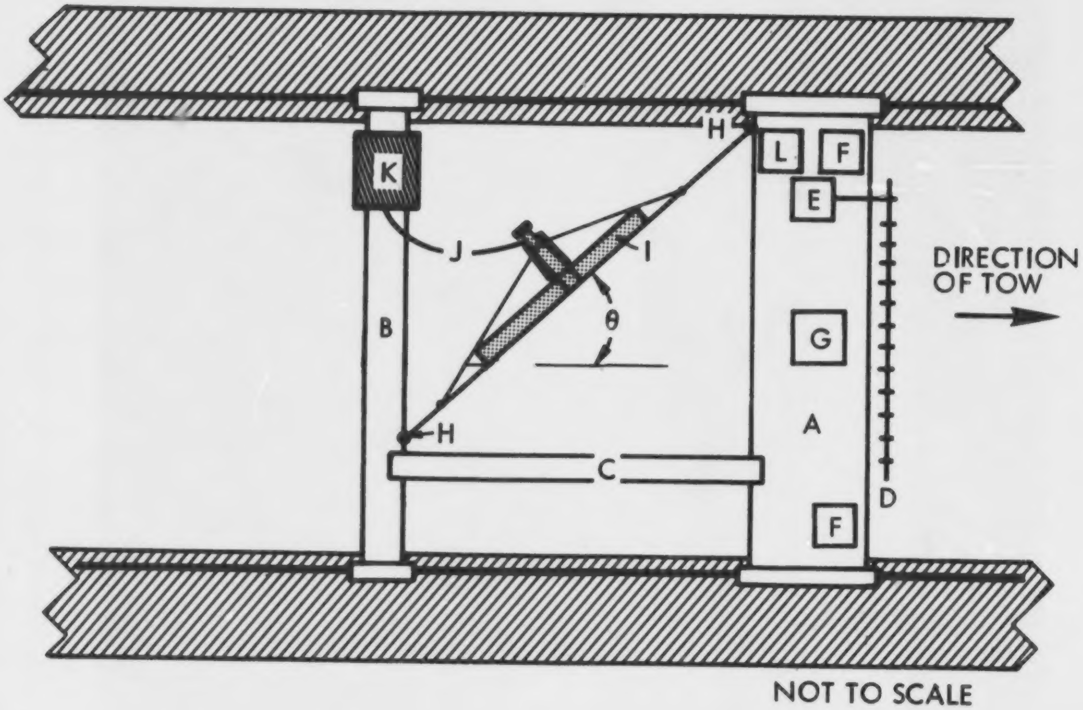
OHMSETT Description

The test facility is a large, unsheltered towing tank specifically intended for the testing and development of devices and techniques for the control of oil and hazardous materials. The primary feature of the facility is the towing basin; overall length 667 feet, 65 feet wide with a water depth of 8 feet. The towing arrangement shown in Figure 21 is comprised of a main and (connected) auxiliary tow bridge capable of tow speeds up to 6-knots. Waves of predetermined lengths and heights can be generated by the hinged-flap wavemaker at the far end of the tank and absorbed by a slat beach at the near end.

The oil distribution system, located on the main bridge, lays down oil slicks of controllable width and thickness in front of the test device. Major components of the system are storage tanks, pumps, flow meters and distributed manifold with movable oil-spreading nozzles (see Figure 21). The location and number of these nozzles controls the width of the slick and its position relative to the test device. The thickness of the slick is controlled by the discharge rate of the pump. In general, the maximum pumping capacity was about 600 gallons per minute, although high viscosity oils reduce the maximum flow rate markedly.

Test Rigging

As shown in Figures 21 and 22, the Air-Jet Boom was deployed between two tow points on the main and auxiliary bridges. One tow cable was connected between a load cell on the main bridge and the left pear ring of the Air-Jet Boom, and the second cable was attached to the right pear ring and to a ratchet hoist on the


H
H
K
L
F
E
J
I
DIRECTION OF TOW
θ
B
G
A
C
D
F
NOT TO SCALE

A	MAIN TOW BRIDGE
B	AUXILARY TOW BRIDGE
C	INTERCONNECTING TRUSS
D	OIL DISTRIBUTION MANIFOLD
E	PUMPS AND FLOW METERS
F	STORAGE TANKS
G	INSTRUMENT AND PERSONNEL SHELTER
H	TOW POINTS
I	AIR BOOM WITH RIGGING
J	AIR HOSE
K	AIR COMPRESSOR
L	PHOTO TOWER

Figure 21. Sketch of OHMSETT towing arrangement and Air Jet Boom rigging.

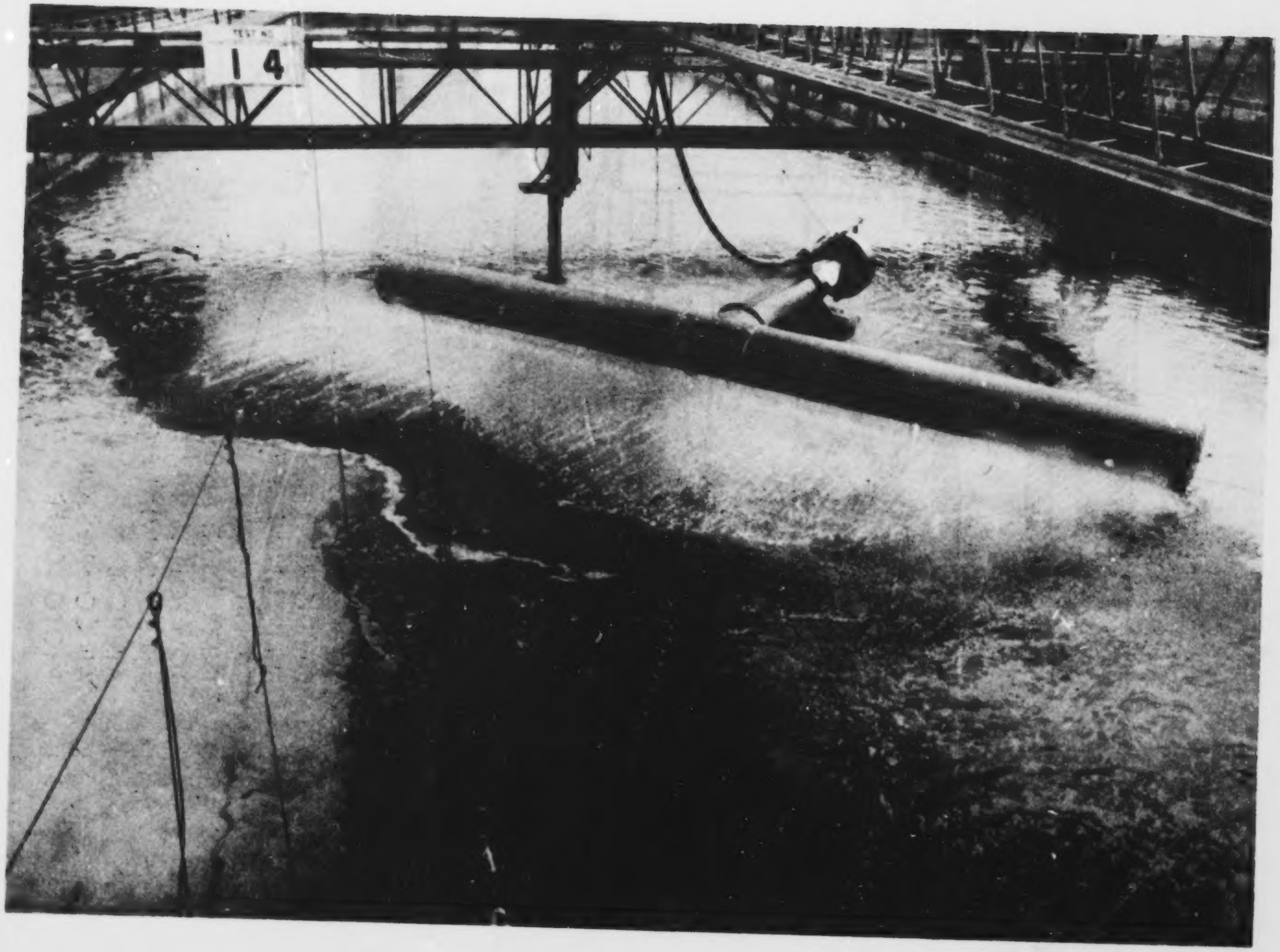


Figure 22. Air Jet Boom rigging for OHMSETT proof tests.
(note air hose connection to jet pump).

auxiliary bridge. The hoist takes up any slack in the rigging and preloads the cables. When placed under a tension of about 1000 pounds, as measured with the load cell, the main cable is suspended approximately 1 foot above the free surface.

The compressor, mounted on the auxiliary bridge, was connected to the jet pump by a length of 2-inch ID compressor hose as shown in Figure 22. Instrument hoses were also supplied to measure the air pressure at the inlet to the jet pump and the pressure inside the boom.

Test Variables

The planned test matrix included two boom deployment angles, 45 degrees and 30 degrees; two test oils, Circo X (Heavy) and Circo XXX (Light); and various tow speeds and sea states. Additional details concerning each test are included in Table 1.

Test Procedure

Tests were usually conducted using the following procedure. Variations from this procedure, necessary in some instances, are given in the Description of Tests.

1. Check the air compressor for proper operation.
2. Record the time and weather conditions (air temperature, water temperature, wind speed and wind direction).
3. Record the supply air pressure at the inlet to the jet pump and the internal boom pressure.
4. Clear the tank area of nonessential personnel.
5. Start the wavemaker, if required.
6. The Test Engineer takes his position in the interconnecting truss above the boom. (Note: During the test run he will estimate the percentage of oil diverted.)
7. Accelerate the bridge to the predetermined tow speed.
8. When desired tow speed is reached, commence oil distribution at the desired flow rate.
9. At the end of the test run, stop oil distribution and tow bridge.
10. Stop wavemaker.
11. Lower skimming bar, idle the air compressor and tow back to starting position, clearing oil from the tank surface.
12. Record tow speed, gallons distributed, time distributed and percentage diverted. Make note of any observations during the test run. Brief test personnel for next test.

TABLE 1. OHMSETT PROOF TESTS MAY 17, 1977 TO MAY 26, 1977

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
1-1	1 1.69	30	C	L	265.5	180	2.2	64	1) Pneumatic barrier used to segregate the diverted oil for measurement (see Fig. 21)) interferred with the performance of the Air Jet Boom. 2) Boom pressure raised from 3.25 to 3.85 in. of water.
1R-1	1 1.69	30	C	L	260.0	180	2.2	72	
2-1	2 3.38	30	C	L	233.0	91	1.9	69	
3-1	4 6.76	30	C	L	208.5	45	1.7	68	
26-1	1 1.69	30	C	H	191.0	180	1.6	100	1) Pneumatic barrier secured diversion estimated by OHMSETT Test Engineer for remaining tests.
27-1	2 3.38	30	C	H	235.2	90	2.0	100	
28-1	3 5.07	30	C	H	222.3	60	1.9	60	
28F-1	3 5.07	30	C	H	225.6	60	1.9	60	Rope supports aft end of jet pump to prevent float sinking.
28R'-1	3 5.07	30	C	H	222.5	60	1.9	60	Additional floatation added to aft end of float. Rope removed.
32-1	1 1.69	30	SR	H	313.0	180	2.6	100	Small regular waves have no effect on performance.
46-1	2 3.38	30	SR	H	227.8	90	1.9	95	
47-1	2.5 4.23	30	SR	H	222.0	72	1.8	80	
48-1	1 1.69	30	MR	H	221.0	180	1.8	100	
49-1	2 3.38	30	MR	H	215.5	90	1.8	95	
50-1	2.5 4.23	30	MR	H	220.0	72	1.8	75	
51-1	3 5.07	30	MR	H	206.0	60	1.7	55	
52-1	1 1.69	30	LHC	H	-	-	-		Inflatable section blew off - loose clamp.

*Number refers to notes at end of the table.

(Continued)

TABLE 1. (Continued)

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
52R-1	1 1.69	30	LHC	H	284.5	180	2.4	95	Uneven oil distribution.
53-1	2 3.38	30	LHC	H	254.0	90	2.1	80	
53R-1	2 3.38	30	LHC	H	267.0	90	2.2	85	
54-1	2.5 4.23	30	LHC	H	213.0	75	1.7	70	
35-1	1 1.69	45	C	H	275.0	180	1.6	100	Boom angle changed to 45 degrees.
36-1	2 3.38	45	C	H	230.0	90	1.4	75	
37-1	2.5 4.23	45	C	H	208.0	72	1.2	20	
55-1	4 6.76	45	C	-	-	-	-	-	No oil. Leading boom leg folds in half at 4 knots. At 4½ to 5 knots the aft section of the jet pump sinks such that water enters bell-mouth floods the boom.
56-1	4.5 7.61	45	C	-	-	-	-	-	
57-1	5 8.45	45	C	-	-	-	-	-	
55R-1	4 6.76	45	C	-	-	-	-	-	
58-1	1 1.69	45	LHC	H	262.5	180	1.5	95	
59-1	2 3.38	45	LHC	H	229.0	90	1.3	75	
60-1	1 1.69	45	MR	H	236.0	180	1.4	100	
61-1	2 3.38	45	MR	H	212.0	90	1.2	60	
62-1	1.5 2.54	45	MR	H	234.0	120	1.4	85	
63-1	1.5 2.54	45	MR	H	445.0	120	2.6	75	Thicker oil slick.
14-1	1 1.69	45	C	L	236.0	180	1.4	100	Change to light oil.

(Continued)

TABLE 1. (Concluded)

1*		2	3	4	5	6	7	8	9,10
OHMSETT Test No.	Tow Speed Knots/FPS	Boom Angle	Wave Condition	Oil Type	Gallons Distributed	Time (Sec)	Calculated Thickness (mm)	Estimated Diversion (%)	Comments
15-1	2 3.38	45	C	L	204.5	90	1.2	75	
16-1	1.5 2.54	45	C	L	256.0	120	1.5	90	
64-1	1 1.69	45	MR	L	246.0	180	1.4	95	
65-1	2.5 4.23	45	MR	L	203.0	90	1.2	15	
66-1	1.5 2.54	45	MR	L	212.0	120	1.2	70	
67-1	1.5 2.54	45	MR	L	138.0	120	0.8	85	Thinner oil slicker.
68-1	1 1.69	45	LHC	L	293.0	180	1.7	95	
69-1	2 3.38	45	LHC	L	-	-	-	-	Because of time limitations oil was not skimmed off the tank. Tests 69-1 and 70-1 indicated good stability and diversion.
70-1	1.5 2.54	45	LHC	L	-	-	-	-	
71-1	1.0 1.69	45	C	L	260.0	180	1.5	100	Sorbent chips added.
72-1	2 3.38	45	C	L	230.0	90	1.4	75	Sorbent chips added.
73-1	-	45	HHC	L	199.5	88	-	-	Speed increased from 1 knot to 2 knots.
73R-1	1 1.69	45	HHC	L	205.0	180	1.2	100	
74-1	1.5 2.54	45	HHC	L	200.0	120	1.2	90	
75-1	2 3.38	45	HHC	L	234.0	90	1.4	50	
76-1	2 3.38	45	HHC	L	265.0	90	1.6	50	Debris added.

(Concluded)

NOTES FOR TABLE 1

1. The first number indicates the test number as planned in the matrix. The letter R following the test number indicates a repeat test. Additional repeat tests are indicated by R'. The last number (1) signifies the OHMSETT Proof Test.

2. The boom angle is measured between the direction of the tow and the longitudinal boom axis (see Figure 21).

3. Wave conditions are as follows:

		H	L	T
C	- calm	0.0	∞	∞
SR	- small regular	0.50'	75'	5.5 sec
MR	- medium regular	0.75'	18'	1.9 sec
LHC	- light harbor chop	2.0'	"Random"	"Random"
HHC	- heavy harbor chop	4.0'	"Random"	"Random"

In wave conditions SR and MR beaches are raised. Tests start as soon as the first wave front passes the boom. In wave condition LHC and HHC beaches are lowered. Tests start after wave generator operates for about 15 minutes. In wave condition C beaches may be raised or lowered.

4. Oil types are as follows:

H - Heavy Test Oil	L - Light Oil
Type: Circo X	Type: Circo XXXX
Viscosity: 755.5 cst @ 70°F	Viscosity: 10.1 cst @ 72°F
Specific Gravity: .936	Specific Gravity: .882
Surface Tension: 35.5 dyns/cm	Surface Tension: 32.4 dyns/cm
Interfacial Tension: 24.6 dyns/cm	Interfacial Tension: 11.9 dyns/cm
Analysis Number (OHMSETT): 67	Analysis Number (OHMSETT): 61

5. Gallons distributed is recorded from the flow totalizer on the main bridge. The flow rate is controlled by the Oil Distribution Operator during the test run to insure that the total volume of oil (precalculated) is distributed in front of the boom.

NOTES FOR TABLE 1. (Continued)

6. Time is the elapsed time of oil distribution recorded with a stop watch by the Oil Distribution Operator.

7. Calculated thickness is computed with the following equation:

$$t_o = \frac{40.6\ G}{VTL \sin \theta}\ (\text{mm})$$

where,

G = gallons distributed
V = velocity (fps)
T = time (seconds)
L = boom length (32 feet)
θ = boom angle (degrees)

This relationship assumes that the slick is evenly distributed over a given area specified by the projected length of the boom (L sin θ) and the distance of the test run (VT). In real conditions, however, the oil slick is not evenly distributed. Variations of thickness are caused by i) changes in flow rate (see Note 5), and ii) the spreading characteristics of the oil from the distribution nozzles.

8. Diversion is determined by the OHMSETT Test Engineer based on his experience and Judgment. The value indicates the portion of the total quantity of oil diverted beyond the trailing edge of the boom.

9. Weather Conditions During OHMSETT Proof Tests - Air temperatures averaged about 70°F during the test period, ranging from about a high of 80°F to a low of 55°F. The barometer was steady at about 29.7 inches of mercury and winds were light, averaging about 5 to 7 knots. Tank water temperatures at the start of the testing was 67°F and steadily increased to 74°F toward the end of the period.

10. Movies and Slides - Movies and slides of the Air-Jet Boom Proof Test may be obtained on request from:

John S. Farlow, Project Officer
Oil and Hazardous Materials Spill Branch
U. S. Environmental Protection Agency
Edison, New Jersey 08817

(Continued)

Description of Tests (see Table 1)

Tests 1-1 Through 3-1:

Comparing observations with measurements of the percentage of oil diverted, it was apparent that surface currents generated by the OHMSETT pneumatic barrier* interfered with the performance of the Air-Jet Boom. Several modifications to reduce the adverse surface current had little effect. One modification, for instance, was to tow a deflection plate under the boom so that it was directly over the barrier, thus blocking the rise of air bubbles near the trailing edge of the boom.

In subsequent tests, the diversion was estimated by the Test Engineer. While this method was somewhat subjective**, it proved to be effective from the standpoint that many more tests could be conducted during the test period since the time-consuming process of recovering the diverted oil for volume measurement was no longer required.

Because of poor performance at the design pressure (3.25 inches of water), the boom's pressure was raised to the maximum pressure (3.85 inches of water) that could be attained with the air compressor (750 SCFM at 58 PSI). Remaining tests were conducted at this pressure.

Tests 26-1 and 27-1***:

It was observed that 100 percent of encountered oil was diverted, whereas in Test 2-1 (with the pneumatic barrier operating), only 69 percent diversion was measured.

Tests 28-1 through 28R'-1:

The aft end of the support float submerged at 3 knots; however, the boom was still operable. In Test 28R-1, a rope was added to hold up the support float. Eventually, the rope was removed and additional flotation was cut to shape and taped to the aft end of the float. The flotation survived the remaining tests.

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*Normally used to segregate diverted from undiverted oil in diversionary boom tests.

**It should be noted that independent, estimated values of diversion by as many as three experienced OHMSETT observers were correlated to within 5 percent as long as the losses did not exceed 25 percent. When oil losses became excessive, the discrepancies were greater. As a rule of thumb, estimated values of diversion below 50 percent are probably only accurate to within 15 or 20 percent.

***Test numbers are based on the planned matrix.

Tests 32-1, 46-1 and 47-1:

Small regular waves (SR were observed to have little effect on boom performance. No further tests were conducted at this sea state.

Tests 48-1 through 51-1:

Medium regular waves (MR) had a marginal effect on boom performance. As compared to Test 27-1, Test 48-1 indicated only a 5 percent reduction in performance.

During Test 52-1, the inflatable section blew off while waiting for the light harbor chop (LHC) to develop (see Figure 23). An inspection revealed that the clamp had loosened. Diversion in the light harbor (Test 53R-1) was 10 percent less than in the medium regular waves (Test 51-1) and 15 percent less than in calm water (Test 27-1).

Tests 35-1 through 37-1:

With the boom deployed at 45 degrees to the flow, diversion decreased significantly. Compared to Test 27-1, the boom at 45 degrees diverted about 25 percent less. At 2.5 knots (Test 37-1), the boom diverted very little oil.

Tests 55-1 through 57-1:

During Test 56-1, the leading inflatable section of the boom was unstable, folding in half near the end of the test run (see Figure 24). The problem was probably caused by the dynamic pressure associated with a bow wave at the leading edge, coupled with increased skin friction drag along the length of the inflatable section. At $4\frac{1}{2}$ knots (Test 47-1), the support float submerged so that water drawn into the jet-pump bellmouth partially flooded the boom. When the speed was subsequently reduced, the inflatable sections bailed the water and reinflated in approximately a minute. No damage was indicated.

Tests 58-1 through 62-1:

In a light harbor chop, the boom (deployed at 45 degrees) diverted as well in waves as in calm water (Test 36-1). In medium regular waves (Test 61-1), however, performance was reduced by 15 percent.

Tests 14-1 through 16-1:

Changed to light oil. A comparison of Test 36-1 with Test 15-1 indicates that there is little change in performance due to differences in the heavy oil and the light oil.

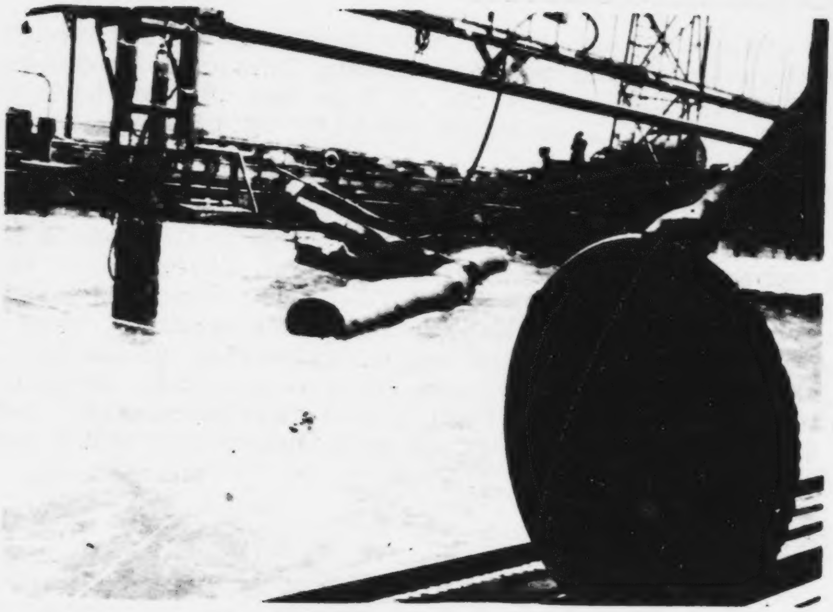

Figure 23. End plate "blown off" of inflatable section.

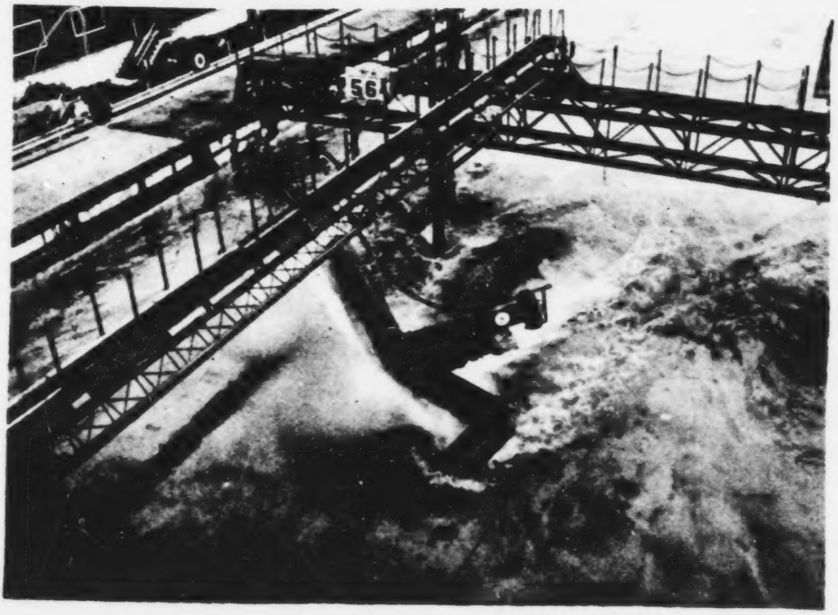

Figure 24. Leading inflatable section folded at five knots.

Tests 64-1 through 67-1:

These tests, compared with Tests 60-1 through 62-1, indicate that in medium regular waves, heavy oil may be diverted more effectively than light oil. This may be due to a greater tendency for light oil to break up with agitation.

Tests 68-1 through 70-1:

A comparison of Test 68-1 with Test 58-1 indicates that oil type does not seem to affect oil diversion. Because of time limitations, Tests 69-1 and 70-1 were conducted using the oil from Test 68-1, which was distributed randomly over the water surface. Hence, estimates of diversion could not be made; however, seakeeping and performance, in general, seemed good. At the highest speed (Test 69-1), the diversion with light oil did not appear to be as great as with heavy oil under comparable conditions.

Tests 71-1 and 72-1:

Oil soaked urethane foam sorbent chips were broadcast on the oil slick in front of the device to demonstrate the feasibility of using the Air-Jet Boom in conjunction with skimmers using the sorbent chip principle. At two knots, all chips were diverted even though only 75 percent of the oil was diverted. The projected "sail" area of the chip above the free surface could have been responsible. Chip diversion at higher speeds (>2 knots) is probably effective.

Tests 73-1 through 76-1:

Final tests were conducted with the heavy harbor chop. Comparing Test 74-1 with Test 16-1, estimated diversion was equivalent to that in calm water. Debris added to the oil slick during Test 76-1 caused no problem. In most cases, debris was blown away by the air-jet or drifted under the inflatable section without snagging.

Summary of Results

The test results, with regard to diversion performance, are summarized in Table 2. Some general observations are:

1. The boom diverted 80 percent of the oil at speeds up to 2½ knots in calm water when the boom was deployed at 30 degrees to the flow.
2. Reduced performance is obtained when the boom was deployed at 45 degrees to the flow.
3. At all boom deployment angles, waves caused little change in performance.

4. Oil-laden sorbent foam chips (Seaward cubes) were diverted without loss at 2 knots.

5. Various types of debris, including shipping pallets, 4-inch by 4-inch timber with nails and partially-filled 5-gallon cans, cleared the boom without snagging or damage.

6. The leading inflatable section folded in half, as shown in Figure 24, at speeds between 4 and 5 knots. This was probably due to high drag forces on the blunt leading edge.

7. At speeds in excess of 4.5 knots, the aft end of the support float submerged, causing water to be drawn into the jet pump, ultimately flooding the boom. When the speed was reduced below 4 knots, the sections fully reinflated in about a minute.

TABLE 2. SUMMARY OF ESTIMATED DIVERSION DURING OHMSETT PROOF TESTS

Boom Angle	Speed (Knots)	Diversion (Estimated)		
		Calm Water	Regular Waves (MR)	Harbor Chop (LHC)
30 degrees (~2-mm slick)	2.0	100%	95%	85%
	2.5	80%	75%	70%
	3.0	60%	55%	-
45 degrees (~1.5-mm slick)	1.0	100%	95%	95%
	1.5	90%	70%	-
	2.0	75%	60%	75%

SECTION 8

MODIFICATIONS

SCOPE

The OHMSETT Proof Test demonstrated that the Air-Jet Boom is structurally stable in currents up to 4 knots. At higher speeds, there were tendencies for the leading inflatable section to fold and for the support float to submerge; but very little diversion was achieved in currents beyond 2.5 knots. Consequently, in terms of modifications to the boom, resolving the high-speed structural problems was felt to be less important than improving the diversion performance.

Parameters Affecting Diversion Performance

Observations made during the OHMSETT Proof Tests indicated that diversion was related to the free surface flow induced by the air jet over a region upstream of the free surface trough, as shown in Figure 4*. The important flow parameters are the mean velocity of the induced flow (v) and its depth (δ). To obtain effective diversion: the induced velocity must be at least equal to or greater than the vector component of tow speed (V), normal to the boom (i.e., $v \geq V \sin \theta$); and the momentum of the induced flow must be at least equal to or greater than the opposing momentum of the approaching oil slick.

Improvements in diversion performance can be expected if the values of v and δ are increased such that the momentum associated with the induced flow is increased**. Increasing both the air-jet size and velocity would, obviously, bolster the free surface flow; but since the air-jet design was assumed to be power limited (i.e., fixed compressor capacity), the problem became one of optimizing the existing air-jet nozzle configuration with regard to its momentum and/or the efficiency of momentum transfer to the surface flow. Parameters that were considered for alteration included: the nozzle impingement angle (α); nozzle height from the free surface (h); and the nozzle throat size (ℓ). A brief description of the experiments is given below.

---

*This is in contrast to the mechanism described by previous investigators (6) who suggest diversion is more directly related to the influence of the free surface trough.

**Momentum is directly proportional to v and δ.

Air-Jet Optimization

Test Setup:

The air-jet optimization tests were conducted in a long, 2-foot wide tank, as shown in Figure 25. A variable geometry air-jet nozzle assembly was mounted at one end of the tank so that the induced flow would be directed toward the opposite end*. The induced velocity flow was determined by measuring elapsed time of travel for spherical floats (specific gravity = 0.95) between a mark at the free surface trough and marks at 6 feet, 8 feet, 10 feet, and 20 feet down the length of the tank. The depth of the induced flow, which is more difficult to determine, was reckoned using various size floats (i.e., 1/4, 1/3, and 3/4 inch diameters).

Test Results:

Tests were conducted with a fixed nozzle throat (ℓ = 3/4 inch) for ten combinations of h, and α, including the existing configuration (h = 5 inch, α = 45 degrees). For each configuration, tests were run for three different diameter floats and repeated three times for each diameter.

The averaged velocity (normalized by the result for the existing configuration) is plotted in Figure 26 as a function of impingement angle with the nozzle height as a parameter. A simple analysis helps give perspective to these test data.

Intuitively, the induced flow should be dependent on the tangential component of the jet velocity (u) at its point of impact on the surface, $u \cos \alpha$, where u is a function of the distance from the jet nozzle $\sim Uf(x)$. For a two-dimensional jet in an infinite medium, $f(x) \propto x^{-n}$, where n is about 1/2. Hence, we may approximate the normalized surface current as a function of α and h (= $x \sin \alpha$):

$$\frac{V}{U} \propto \cos \alpha \sqrt{\frac{\sin \alpha}{h}}$$

---

*Because of time and cost restraints, not all parameters could be considered. In particular, the setup does not account for the effects of tow speed, V , or deployment angle (θ = 90 degrees). Moreover, because the tank is closed, test runs had to be brief to limit recirculating flow. Nevertheless, the experiment, while simplified in many ways, lent some insight into the comparative importance of the nozzle parameters.

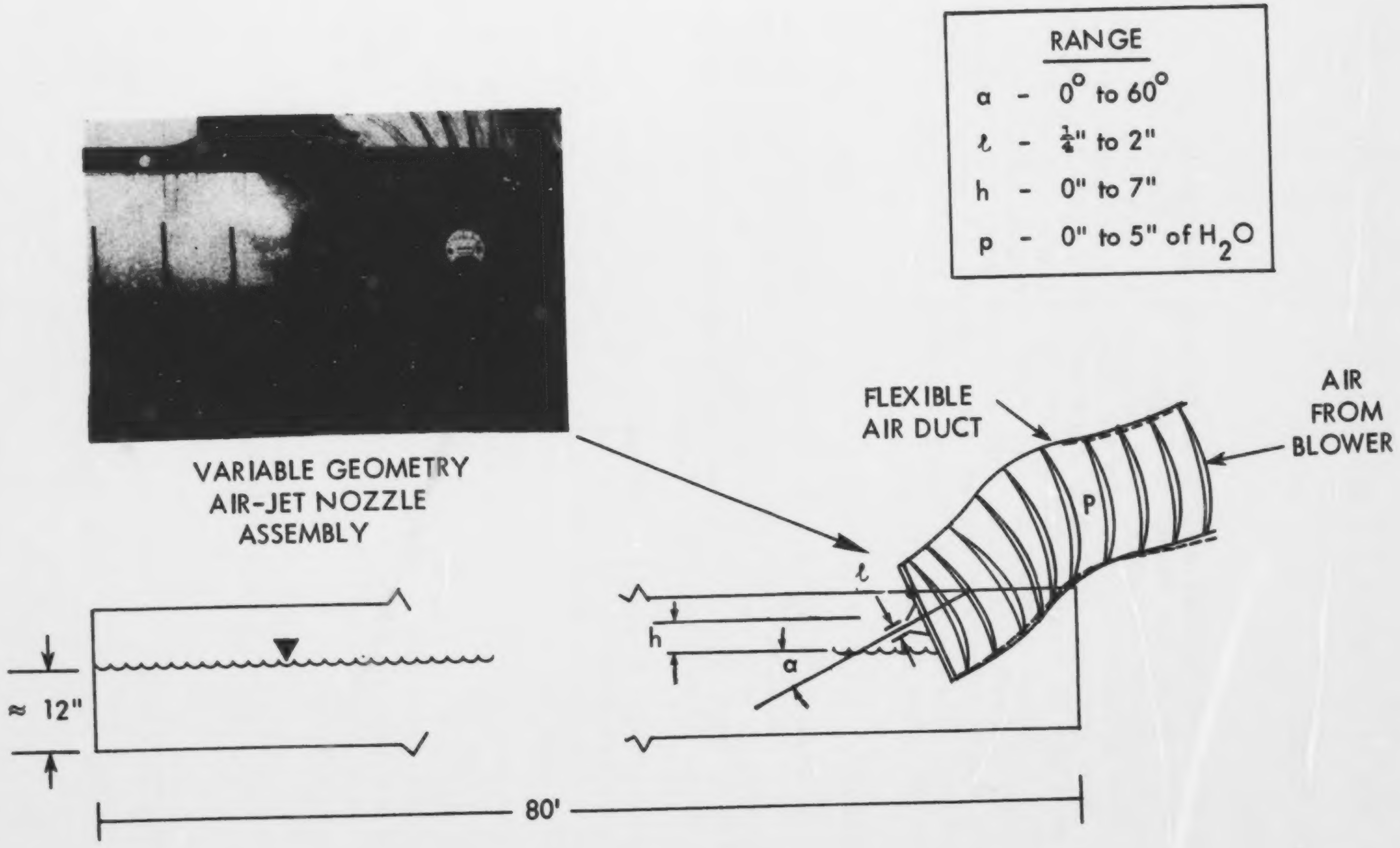
RANGE
α - 0° to 60°
ℓ - ¼" to 2"
h - 0" to 7"
p - 0" to 5" of H₂O
VARIABLE GEOMETRY AIR-JET NOZZLE ASSEMBLY
FLEXIBLE AIR DUCT
AIR FROM BLOWER
P
ℓ
h
α
≈ 12"
80'

Figure 25. Test setup for air-jet nozzle optimization.

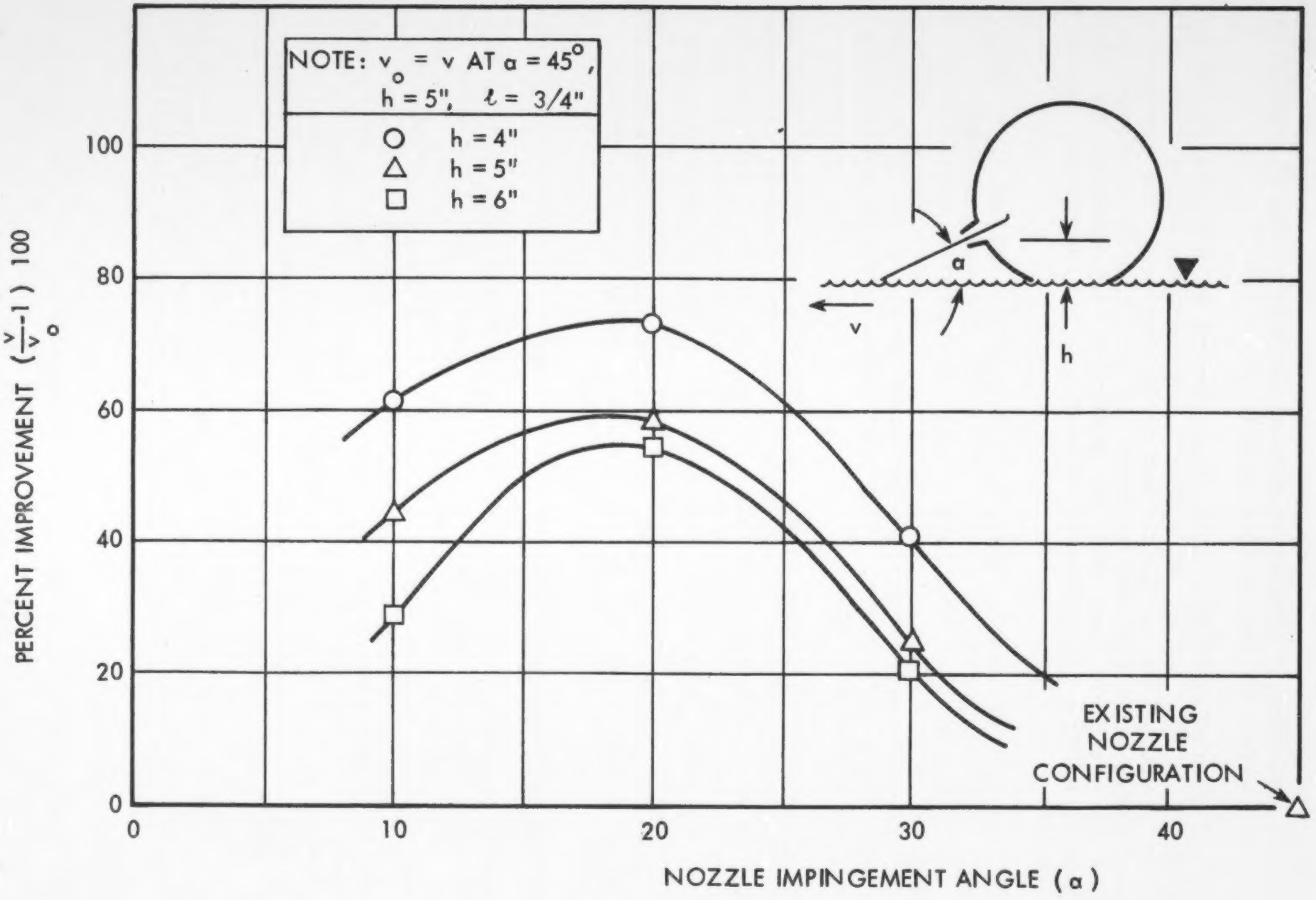

Figure 26. Effect of nozzle height and impingement angle on the average induced current. (Summary of test results).

This indicates that an optimum impingement angle would be around 35 degrees and that h should be minimized (to bring the point of impingement close to the nozzle exit).

The measured currents show improvement with decreased h (on the order of $h^{-\frac{1}{2}}$). Also, an optimum impingement angle does exist, but it is found to be on the order of 20 degrees; the simple analysis above does not account for the efficiency of momentum transfer or the fact that the jet momentum is conserved as the jet expands before impingement; therefore, a discrepancy could be anticipated.

The effect of nozzle throat size was determined in a similar way. Three different nozzle throat sizes were tested: 1 inch, $1\frac{1}{4}$ inch and $1\frac{1}{2}$ inch, each using an improved nozzle configuration: h = 4 inch, α = 20 degrees. Adjustments of internal air pressure were required for each nozzle size to maintain a constant (air-jet) power. The theoretical relationship that was used is given in Figure 27.

The test results are shown in Figure 28 and reveal that the larger the nozzle throat size, the better. This stands to reason because of the attending increase of momentum (at fixed power) as shown in Figure 27. Increases in nozzle size cannot be unbounded, however, since the internal air pressure provides the boom's structural support. Clearly, if the nozzle should be too large and the pressure too low, the inflatable section would fold at a speed lower than the speed limiting effective diversion. This problem is considered further below.

Inflatable Section Modification

By reanalyzing the structural calculations of Appendix D, we estimated that to maintain a nominal degree of structural stability, the maximum nozzle throat size (for h = 4 inch, α = 20 degrees) should be limited to $1\frac{1}{4}$ inch with 3 inches of water pressure. Calculations in Appendix D also indicate improved wave conformance with this configuration. Therefore, we recommend that a new set of inflatable sections be fabricated with this throat size ($1\frac{1}{4}$ inch). However, because of the lower margin of structural stability with the $1\frac{1}{4}$ inch nozzle, a second set of inflatable sections was also fabricated with the 3/4 inch nozzle (h - 4 inch, α = 20 degrees) which offers improved stability. Comparisons would then be made between the two modified nozzle configurations (see Table 3) during the OHMSETT Performance Tests with regard to diversion efficiency and stability.

Fairing Modification

To limit folding of the inflatable section at high speed, a fairing (shown in Figure 11a) was added to reduce the drag coefficient of the otherwise blunt end of the inflatable section.

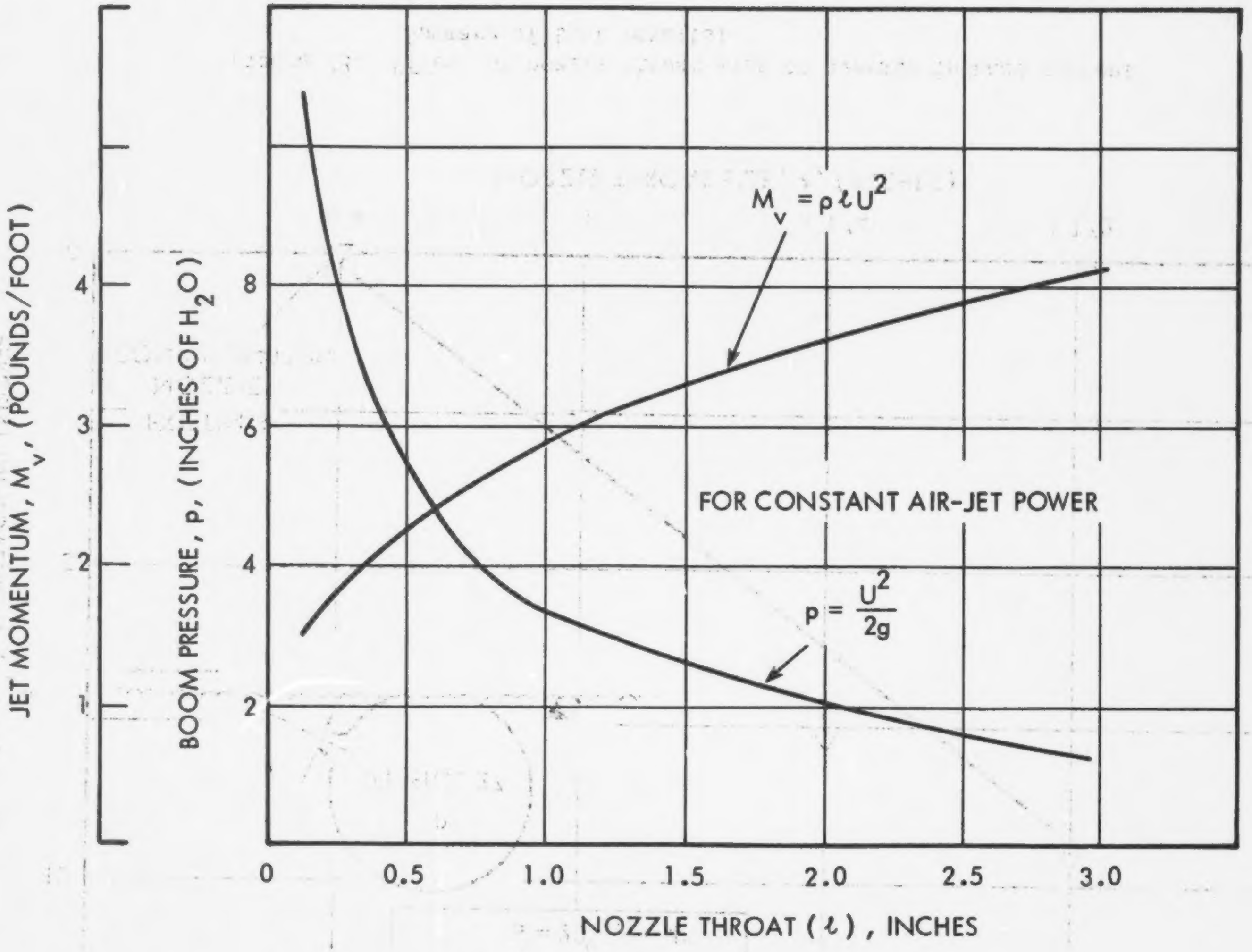

Figure 27. Effect of nozzle throat size on the jet momentum and boom pressure for constant power.

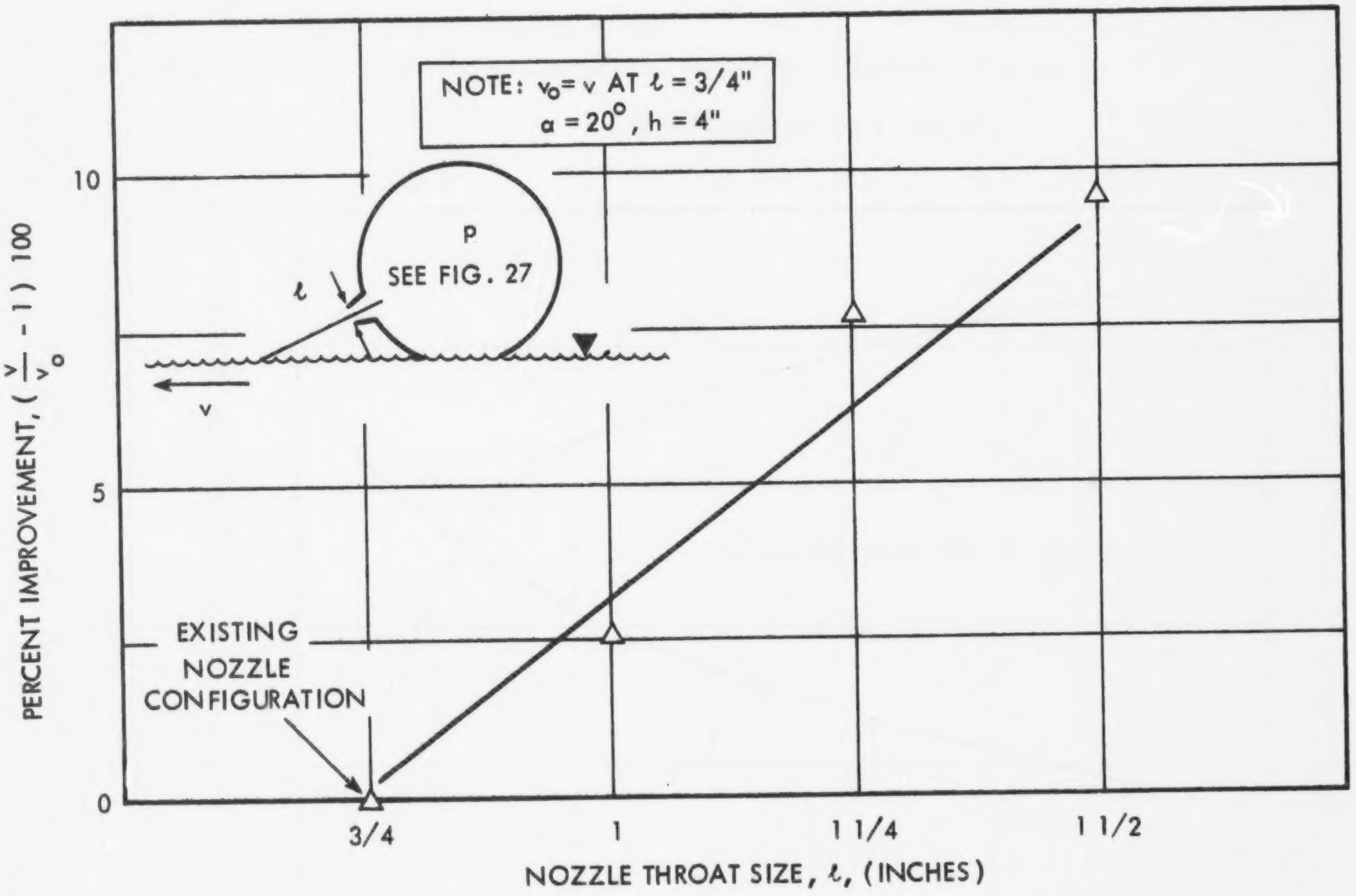

Figure 28. Effect of nozzle throat size on average induced current. (Summary of test results).

TABLE 3. SUMMARY OF NOZZLE CONFIGURATIONS

Nozzle Designation	Boom Pressure, P (inches of water)[+]	Impingement Angle, α (degrees)	Nozzle Throat, ℓ (inches)	Nozzle Height, h (inches)	Structural Stability[*]	Wave Conformance[*]	Diversion Performance[*]
3/4" - 45° (existing)	3.85	45	3/4	5	3	1	1
3/4" - 20° (modified)	3.85	20	3/4	5	2	2	2
1-1/4"-20° (modified)	3.00	20	1-1/4	4	1	3	3

[+] Constant air horsepower per foot of boom.

[*] 1-least, 2-better, 3-best.

Fiberglas-covered foam construction was used to reduce weight.

Other solutions to prevent folding, such as shock cords or cables, were considered unsuitable because stress transferred to the fabric could cause tearing or hinder wave conformance.

Support Float Modification

Additional reserve flotation was installed to prevent submergence of the support float at high speed*. The center area between the two hulls was filled with foam and covered with sheet metal. More flotation was also added at the aft end of the support float, as shown in Figure 29. Weights were placed in the forward end of the support float to compensate for the change in trim. A clamping arrangement was also fitted to allow attachment of the air supply hose so that it was free floating, as shown in Figure 29.

Clamping Modification

A small lip, shown in Figure A-4 in Appendix A, was added to improve the attachment of the fabric to the center section and end plate.

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*This approach is more of a stop-gap measure than a real solution, since the problem concerns hull design.

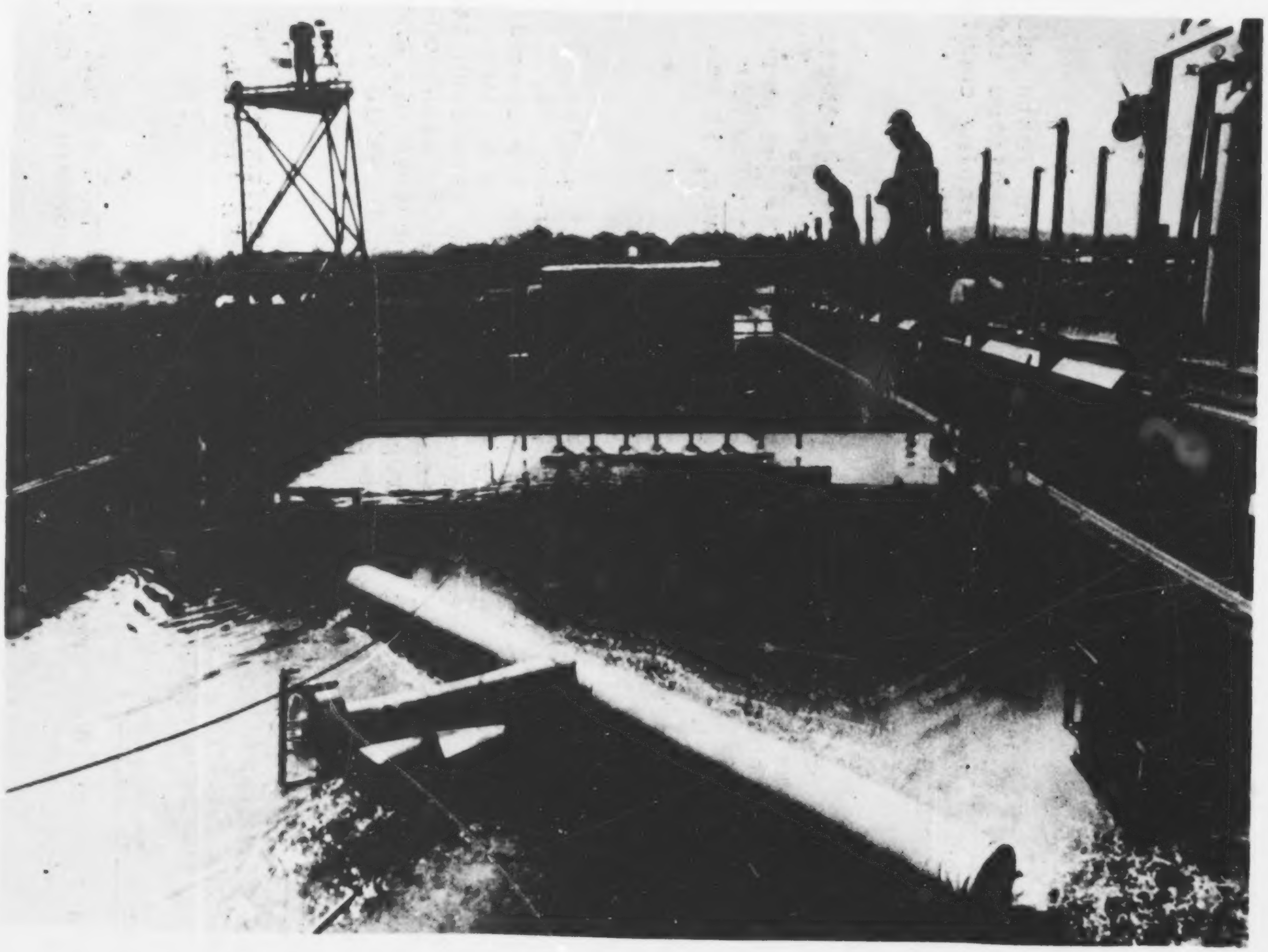

Figure 29. Air jet boom rigging for OHMSETT performance tests. (Note air hose connection to jet pump).

SECTION 9

OHMSETT PERFORMANCE TESTS

GENERAL OBJECTIVES

The general objective of the OHMSETT Performance Tests was to evaluate the performance characteristics of the modified Air-Jet Boom under a wider and more severe range of operating conditions than encountered during the OHMSETT Proof Tests.

Test Rigging

The rigging of the Air-Jet Boom for the Performance Tests was nearly the same as it was for the earlier Proof Tests. The high-pressure air hose was connected directly to the jet pump so that the hose was free floating (see Figure 29). The air compressor was from a different manufacturer; however, it was equal in rated capacity and pressure.

Test Variables

The test matrix included three boom deployment angles, 45 degrees, 30 degrees, and 20 degrees; two types of test oil, Circo X (Heavy) and Circo XXXX (Light); and various tow speeds and sea states, including the 4-foot harbor chop. In a few tests, air pressure inside the boom was reduced to establish its effect on performance characteristics. Additional details concerning the tests, including the properties of the test oil and the weather conditions during the test, are given in Table 4.

Test Procedures

Procedures used for the Performance Tests are the same as outlined in Section 7. Variations from this routine are described in the Description of Tests.

Description of Tests

Data from the Performance Tests is given in Tables 4 and 5. A brief description of the tests (in chronological order) is given below:

Tests 1-2 through 9-2:

TABLE 4. OHMSETT PERFORMANCE TESTS
October 5, 1977 to October 13, 1977

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
1-2	0-6 0-10.14	45	C	-	-	-	-	-	Tests 1-2 through 9-2 conducted with 3/4"-20° nozzle.
4-2	1 1.69	45	C	H	294	180	1.7	100	
5-2	2 3.38	45	C	H	265	90	1.6	60	Uneven oil distribution.
6-2	1.5 2.54	45	C	H	240	120	1.4	100	Trace loss.
7-2	2 3.38	45	C	H	131	90	0.8	75	
8-2	1.5 2.54	45	HHC	H	201	90	1.6	75	
8A-2	1 1.69	45	HHC	H	266	180	1.6	100	Trace loss.
9-2	1.5 2.54	45	MR	H	264	120	1.6	75	
10-2	1.0 1.69	45	C	H	244	180	1.4	100	Changed inflatable section to 1¼"-20° nozzle.
11-2	2 3.38	45	C	H	264	90	1.6	70	
12-2	1.5 2.54	45	C	H	273	120	1.6	100	Trace loss.
13-2	2 3.38	45	C	H	132	90	0.8	90	
14-2	1.5 2.54	45	MR	H	251	120	1.5	80	
15-2	1.5 2.54	45	HHC	H	237	120	1.4	80	
15A-2	1.5 2.54	45	HHC	H	147	120	0.9	90	
16-2	1.5 2.54	30	C	H	328	120	2.7	100	Remaining tests conducted with 1¼"-20° nozzle.
17-2	2 3.38	30	C	H	234	90	1.9	100	Trace loss.

*Number refers to notes at end of the table.

(Continued)

TABLE 4. (Continued)

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
18-2	2.5 4.23	30	C	H	232	72	1.9	90	
18A-2	3 5.07	30	C	H	232	60	1.9	75	
19-2	2 3.38	30	HHC	H	270	120	1.7	90	
19A-2	3 5.07	30	HHC	H	111	60	1.9	80	
20-2	2 3.38	30	MR	H	219	90	1.8	95	
46-2	1.0 1.69	30	C	H	698	180	5.8	95	Thicker oil slick.
47-2	2.0 3.38	30	C	H	348	90	2.9	95	Thicker oil slick.
31-2	1.5 2.54	30	C	L	221	121	1.8	100	
32-2	2.5 4.23	30	C	L	217	72	1.8	70	Uneven oil distribution.
33-2	3.0 5.07	30	C	L	98	60	0.8	70	
34-2	2.0 3.38	30	MR	L	219	90	1.8	60	
34A-2	3 5.07	30	HHC	L	115	60	1.0	-	Leading inflatable section folded in half.
35-2	2.0 3.38	30	HHC	L	224	90	1.9	70	
35R-2	2.0 3.38	30	HHC	L	220	90	1.8	80	
35A-2	3.0 5.07	30	C	L	111	60	0.9	60	Uneven oil distribution.
36-2	1.5 2.54	30	C	L	218	120	1.8	100	Trace loss.
37-2	2 3.38	45	C	L	246	90	1.4	75	

(Continued)

TABLE 4. (Continued)

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
38-2	2 3.38	45	C	L	122	90	0.7	90	Variable diversion thin slick.
38R-2	2 3.38	45	C	L	219	90	1.3	60	Uneven oil distribution.
39-2	1.5 2.54	45	HHC	L	266	120	1.6	60	
39A-2	1 1.69	45	HHC	L	116	180	0.7	100	Trace loss.
40-2	1.5 2.54	45	MR	L	229	120	1.3	70	
40A-2	1.5 2.54	45	MR	L	126	120	0.7	80	
48-2	2 3.38	30	C	L	224	90	1.9	100	
48R-2	2 3.38	30	C	L	265	90	2.2	95	
49-2	3 5.07	30	C	L	217	60	1.8	80	
50-2	4 6.76	30	C	L	213	45	1.8	50	
50A-2	4.5 7.61	30	C	L	118	40	1.0	30	
51-2	1 1.64	30	C	L	598	180	5.0	100	
52-2	2 3.38	30	C	L	348	90	2.9	90	
53-2	4 6.76	30	C	L	227	45	1.9	60	
54-2	3 5.07	30	C	L	231	60	1.9	80	
32R-2	2.5 4.23	30	C	L	271	80	2.0	80	
32A-2	2.5 4.23	30	C	L	204	75	2.2	100	12' wide slick aligned with trailing edge of boom, trace loss.

(Continued)

TABLE 4. (Concluded)

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
55-2	2.5 4.23	30	C	L	147	75	3.1	100	6' wide slick aligned with trailing edge of boom, no loss.
56-2	3.5 5.92	30	C	L	110	53	2.2	100	6' wide slick aligned with trailing edge of boom, trace loss.
57-2	4 6.76	30	C	L	92	45	2.0	100	6' wide slick aligned with trailing edge of boom, trace loss.
57A-2	4 6.76	30	C	L	94	45	2.0	60	6' wide slick aligned with leading edge of boom.
56A-2	3.5 5.92	30	C	L	110	53	2.3	65	6' wise slick aligned with leading edge of boom.
49A-2	3 5.07	30	C	L	208	60	2.1	90	12' wide slick aligned with trailing edge of boom - see test 49-2.
58-2	1 1.69	30	C	L	358	180	3.0	100	Supply pressure reduced to 24 psi.
58A-2	1 1.69	30	C	L	358	180	3.0	100	Supply pressure reduced to 11 psi.
58B-2	1 1.69	30	C	L	358	180	3.0	70	Supply pressure reduced to 1 psi.
59-2	1.5 2.54$	30	C	L	240	120	2.0	100	Trace loss.
59A-2	1.5 2.54	30	C	L	240	120	2.0	80	Supply pressure reduced to 20 psi.
59B-2	1.5 2.54	30	C	L	240	120	2.0	50	Supply pressure reduced to 7 psi.
60-2	1.5 2.54	30	C	L	240	120	2.0	100	Debris added.
61-2	3 5.07	30	C	L	208	60	1.7	85	

(Concluded)

TABLE 5. OHMSETT PERFORMANCE TESTS
NOVEMBER 2, 1977 TO NOVEMBER 10, 1977

1* HMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
1-3	1.5 2.54	20	C	H	243	120	3.0	100	
2-3	2.0 3.38	20	C	H	230	90	2.8	100	Trace loss.
3-3	3.0 5.07	20	C	H	202	60	2.5	90	
4-3	4.0 6.76	20	C	H	220	45	2.7	70	
5-3	2.0 3.38	20	C	H	468	90	5.7	90	
6-3	2.0 3.38	20	HHC	H	241	90	3.0	90	
7-3	3.0 5.07	20	HHC	H	260	60	3.2	80	
8-3	3.0 5.07	20	MR	H	270	60	3.3	90	
9-3	4.0 6.76	20	MR	H	-	-	~3.0	70	Data not recorded.
10-3	1.5 2.54	20	C	L	218	120	2.7	100	
11-3	2.0 3.38	20	C	L	234	90	2.9	100	Trace loss.
12-3	3.0 5.07	20	C	L	224	60	2.7	90	
13-3	4.0 6.76	20	C	L	265	45	3.2	-	Support float submerged.
14-3	2.5 4.23	20	C	L	439	72	5.4	80	
15-3	2.5 4.23	20	MR	L	230	72	2.8	100	Trace loss.
16-3	3.0 5.07	20	MR	L	234	60	2.9	85	
17-3	3.0 5.07	20	HHC	L	258	61	3.1	75	

(Continued)

TABLE 5. (CONCLUDED)

1* OHMSETT Test No.	Tow Speed Knots/FPS	2 Boom Angle	3 Wave Condition	4 Oil Type	5 Gallons Distributed	6 Time (Sec)	7 Calculated Thickness (mm)	8 Estimated Diversion (%)	9,10 Comments
18-3	2.0 3.38	20	HHC	L	233	90	2.8	80	Nov. 7 - Winds 20-25 knots and heavy rain - tests resumed Nov. 9.
19-3	1.0 1.69	20	C	L	456	192	5.2	100	Supply pressure reduced to 27 psi.
20-3	1.0 1.69	20	C	L	343	181	4.2	100	Supply pressure reduced to 10 psi, trace loss.
21-3	1.0 1.69	20	C	L	276	219	2.8	100	Supply pressure reduced to 5 psi, trace loss.
22-3	3.0 5.07	20	C	L	199	58	2.5	85	Supply pressure reduced to 35 psi.
23-3	3.0 5.07	20	C	L	233	60	2.8	80	Supply pressure reduced to 25 psi.
24-3	3.0 5.07	20	C	L	209	60	2.6	80	Supply pressure reduced to 20 psi.
25-3	3.0 5.07	20	C	L	125	35	2.6	-	Supply pressure reduced to 10 psi, leading leg folded.
26-3	3.0 5.03	20	C	L	224	60	2.7	50	Supply pressure reduced to 15 psi.
27-3	2.0 3.38	20	C	L	232	91	2.8	100	Supply pressure reduced to 25 psi.
28-3	2.0 3.38	20	C	L	239	90	2.9	85	Supply presure reduced to 10 psi.
29-3	2.0 3.38	20	C	L	228	90	2.8	80	Supply pressure reduced to 5 psi.
30-3	2.0 3.38	20	HHC	L	240	90	2.9	70	Supply pressure reduced to 35 psi.
31-3	-	20	HHC	L	-	-	-	-	Supply pressure reduced to 25 psi, end plate pulled off.
32-3	2.0 3.38	20	MR	L	227	90	2.8	100	Supply pressure reduced to 35 psi, trace loss.
33-3	2.0 3.38	20	MR	L	230	90	2.8	90	Supply pressure reduced to 10 psi.
34-3	2.0 3.38	20	MR	L	230	90	2.8	50	Supply pressure reduced to 5 psi.
35-3	3.0 5.07	20	MR	L	122	60	1.5	85	Supply pressure reduced to 25 psi. (Concluded)

NOTES FOR TABLES 4 AND 5

1. The first number indicates the test number as planned in the original test matrix. The letter R indicates a repeated test. The letters A, B, C, etc. indicates a variation of the preceding test. The last number (2 or 3) signifies that the test is from the OHMSETT Performance Tests.

2. The boom angle is measured between the direction of tow and the longitudinal boom axis (see Figure 21).

3. Wave conditions are as follows:

		H	L	T
C	- calm	0.0	∞	∞
MR	- medium regular 1	0.75'	18'	5.5 sec
HHC	- heavy harbor chop	4.00'	"random"	"random"

For wave condition MR, the beaches are raised. Tests start after the wave generator operates for about 8 minutes. (This makes the waves somewhat higher and steeper than the MR wave condition for the Proof Tests.) For wave conditions LHC and HHC beaches are lowered. Tests start after the wave generator operates for about 15 minutes. For condition C beaches may be raised or lowered.

4. Oil types are as follows:

H - Heavy Test Oil

Type: Circo X
Viscosity: 893 cst @ 70°F
Specific Gravity: .938
Surface Tension: 36.0 dynes/cm
Interfacial Tension: 15.4 dynes/cm
Analysis Number (OHMSETT): 409

L - Light Test Oil

Type: Circo XXXX
Viscosity: 15.4 cst @ 70°F
Specific Gravity: .899
Surface Tension: 30.9 dynes/cm
Interfacial Tension: 14.3 dynes/cm
Analysis Number (OHMSETT): 416

5. Gallons distributed is recorded from the flow totalizer on the main bridge. The flow rate is controlled by the Oil Distribution Operator during the test run to insure the total volume of oil (precalculated) is distributed in front of the boom.

(Continued)

NOTES FOR TABLE 4 AND 5. (Concluded)

6. Time is the elapsed time of oil distribution recorded with a stop watch by the Oil Distribution Operator.

7. Calculated thickness is computed with the following equation:

$$t_o = \frac{40.6\ G}{VTL \sin \theta}\ (\text{mm})$$

where,

G = gallons distributed
V = velocity (fps)
T = time (seconds)
L = boom length (38 feet)
θ = boom angle (degrees).

This relationship assumes the slick is distributed over a given area specified by the projected length of the boom (L sin θ) and the distance of the test run (VT). In real conditions, however, the oil slick is not evenly distributed. Variations of thickness are caused by i) changes in flow rate (see Note 5), and ii) the spreading characteristics of oil from the distribution nozzles to the water surface (see Figure 29).

8. Estimated diversion is determined by the OHMSETT Test Engineer based on his experience and judgment. The value indicates the portion of the total quantity of oil diverted beyond the trailing edge of the boom.

9. Weather Conditions during OHMSETT Performance Tests - The weather was generally chilly. Air temperature averaged about 50°F during the tests ranging from a high of 62°F to a low of 48°F. During some tests oil in the tow bridge storage tanks was heated to get proper flow rate and distribution on the free surface. The barometer was steady and winds were light averaging 0-5 knots. Tank water temperature generally averaged around 58°F.

10. Movies and Slides - Movies and slides of the Air-Jet Boom Performance Tests may be obtained on request from: John S. Farlow, Project Officer
Oil and Hazardous Materials Spill Branch
U. S. Environmental Protection Agency
Edison, New Jersey 08817

Tests started using the modified 3/4-inch-20 degree nozzle configuration. The boom was deployed at 45 degrees and heavy oil was used. Poor diversion during Test 5-2 was probably due to uneven oil distribution or poor alignment of the oil slick with the leading edge of the boom.

Tests 10-2 through 15A-2:

The inflatable sections were changed to the 1¼-inch-20 degree nozzle configuration. Compared with the previous runs, performance was improved. For example, compare Test 7-2 with Test 13-2, where diversion improved from 75 percent to 90 percent, respectively.

Tests 16-2 through 20-2:

The deployment angle was changed from 45 to 30 degrees. At 2 knots (Test 18-2), the boom diverted a 1-millimeter slick with 100 percent efficiency. With the same slick thickness at 3 knots in a 4-foot harbor chop (Test 19A-2), the boom diverted about 80 percent.

Tests 46-2 and 47-2:

These tests indicate that slicks up to 6 millimeter can be diverted effectively (95 percent) at 1 knot, and a 3-millimeter slick can be diverted with the same performance at 2 knots.

Tests 31-2 through 36-2:

Increased wind speed and a change in direction caused the oil slick to shift alignment with the leading edge of the boom. During Test 34A-2, the fairing on the inflatable section "dug" into a wave, causing the section to fold. These tests were repeated later.

Tests 37-2 through 40A-2:

These tests were conducted at 30 degrees with light oil. Tests 53-2 and 54-2 indicated that 80 percent of the oil could be diverted at 3 knots, whereas 60 percent was diverted at 4 knots. Test 51-2 showed that a 5-millimeter slick could be diverted at 1 knot with no loss. A 3-millimeter slick could be diverted at 2 knots with about 10 percent loss.

Tests 32R-2 and 32A-2:

Test 32R-2 was repeated because of poor alignment of the leading edge of the boom with the oil slick. With proper slick alignment, diversion improved to 80 percent. Test 32A-2 was conducted to further investigate the importance of slick alignment. Using the conditions of Test 32R-2, Test 32A-2 was conducted with a 12-foot wide oil slick so that it was aligned with the trailing edge of the boom and with the opposite edge of the slick 3 feet within the leading edge of the boom. Comparing Test 32R-2 with 32A-2, diversion increased to 100 percent. Therefore, it is probable that oil losses are greatest near the leading edge of the boom.

Tests 55-2 through 57A-2:

These tests also indicate how important slick alignment is. Compare, for example, Test 56-2 with Test 56A-2 or Test 57-a with Test 57A-2.

Tests 58-2 through 59B-2:

The following test demonstrated the effect of reduced air supply pressure. Pressures as low as 1 PSI were supplied to the jet pump (Test 58B-2). The correlation between inlet pressure to the jet pump and compressor capacity is given in Figure 7.

Test 60-2:

Various types of debris including wood pallets, timber with nails, milk boxes and 5-gallon cans were tossed off the tow bridge in the path of the boom. In the case of debris with high freeboard (e.g., milk box), the boom "blew" the debris away from the boom, whereas debris with low freeboard (e.g., timber) passed underneath the boom without snagging.

Test 61-2:

Test 61-2 was similar to Test 54-2, except the slick thickness was reduced. Diversion increased from 80 percent to 85 percent.

NOTE: Performance tests were continued on November 2, 1977. (Table 5)

Tests 1-3 through Test 9-3:

The boom deployment angle was changed to 20 degrees. at 4 knots, the boom diverted a 3-millimeter slick with 70 percent efficiency. When the tow speed was reduced to 3 knots, the efficiency increased to 90 percent (Test 3-3). With the addition of the medium regular waves, the performance was unaffected at both 3 and 4 knots.

Tests 10-2 through 17-3:

With light oil, performance was generally the same as with heavy oil. During Test 13-3, the float submerged at 4 knots.

Test 18-3:

This test is of special interest because it was conducted during high winds and heavy rain. Compared to Test 6-3, which was conducted in calm weather, diversion performance was reduced by 10 percent to 80 percent efficiency.

Test 19-3 through 35-3:

These tests were conducted at reduced operating pressures. Using pressure as low as 5 PSI, 100 percent efficiency was obtained at 1 knot (Test 21-3). Increasing the current to 2 knots, the efficiency dropped to 80 percent (Test 29-3). The addition of medium regular waves, however, reduced performance markedly to 50 percent, pointing out the importance of air pressure from the standpoint of structural support (Test 34-3).

Summary of Results

Test results are summarized in Table 6. The performance of the modified boom was improved, compared to the results of the Proof Tests (Table 2). It should be noted, however, that comparisons between the Performance Tests and the Proof Tests, based only on estimated diversion, are not totally reliable since there were several differences in the test conditions; for example, the weather conditions. Cold weather during the Performance Tests caused the oil distribution over the free surface to be uneven (heating the oil in the bridge storage tanks prior to distribution tended to partially reduce this problem). Differences in the wave conditions and in the test oils are noted in Tables 1, 4 and 5.

Some general observations are:

1. The $1\frac{1}{4}$-inch-20 degree nozzle was better than the 3/4-inch-45 degree nozzle. For example, at 3 knots, the boom, when deployed at 30 degrees to the flow, diverted 85 percent, whereas during the Proof Test, only 60 percent was diverted.

2. Increased performance is also obtained when the boom is deployed at 20 degrees to the flow.

3. Wave conformance (and therefore diversion efficiency) improved with the $1\frac{1}{4}$-inch-20 degree nozzle because of lower internal air pressure.

4. Oil losses at the higher speed range (>2 knots) occurred predominately along the first 2 or 3 feet of the boom from the leading edge. Loss also occurred near the center section, although to a much lesser extent.

TABLE 6. SUMMARY OF ESTIMATED DIVERSION DURING OHMSETT PERFORMANCE TESTS

Boom Angle	Speed (Knots)	Diversion (Estimated)		
		Calm Water	Regular Waves (MR)	Harbor Chop (HHC)
20 Degrees (~3-mm slick)	2.0	100%	-	90%
	3.0	90%	90%	80%
	4.0	70%	70%	-
30 Degrees (~2-mm slick)	2.0	100%	95%	90%
	2.5	90%	-	-
	3.0	85%	-	80%
45 Degrees (~1.5-mm slick)	1.0	100%	-	100%
	1.5	100%	80%	80%
	2.0	75%	-	-

5. The fairing, mounted on the leading edge of the boom, prevented folding up to 6 knots with the 3/4-inch-20 degree nozzle. Using the $1\frac{1}{4}$-inch-20 degree nozzle, the maximum tow speed was just under 5 knots.

6. The modifications to the support float enable it to be towed at slightly higher speeds. When deployed at 20 degrees to the flow, however, the support float was unstable at 4 knots and did flood on one occasion.

7. Changing to the clamping arrangement prevented the inflatable section from "blowing off".

8. No damage occurred during the debris test even though it was much more severe than during the Proof Tests.

9. Tests with reduced compressor input demonstrated that 100 percent diversion can be obtained at 1½ knots (30-degree deployment), using only 80 percent of the total available compressor capacity.

SECTION 10

DISCUSSION OF RESULTS

PERFORMANCE RESULTS

Calm Water

Results of the OHMSETT calm water tests clearly indicate the strong dependence of diversion performance on the tow speed V, deployment angle θ and slick thickness t_o. The effect of the oil slick's viscosity is comparatively insignificent. Diversion estimates presented in Figures 30, 31 and 32 (for both heavy and light oil) show the tendency for performance to decline steadily with increased speed, steeper deployment angle and thicker oil slicks. Figure 33 further summarizes the calm water performance of the air-jet boom by plotting only the results for 100 percent and 90 percent diversion* against the normal velocity component (V sin θ) and the slick thickness.

Figure 33 is of special interest because it delineates the general limits of performance. Specifically, conditions falling to the left of the curve indicates complete diversion with "no loss"; whereas conditions to the right represent increasing losses (greater than 10 percent). The curve also suggests that the maximum speed obtainable without loss (i.e., for very thin slicks, t_o~0) is about 1.5 knots/sin θ (or 4.4 knots at a 20-degree deployment angle).

Waves

The performance of the boom in waves is nearly the same as it is in calm water (see Table 6). Loss rates in waves generally exceed calm water losses by about 5 to 10 percent. To a large extent, this insensitivity to waves is attributable to the boom's structural and seakeeping characteristics. The orientation of the air jet is properly maintained, despite the changing height and slope of the free surface. The air-jet's interaction with the oil slick is slightly different in waves than in calm water because of the boom's response to the orbital velocities that give rise to surge motions. In effect, the surface current becomes unsteady, causing the oil slick to be diverted in progressive "sweeps". This "sweeping action" may contribute to greater

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*Note: These results have the highest accuracy.

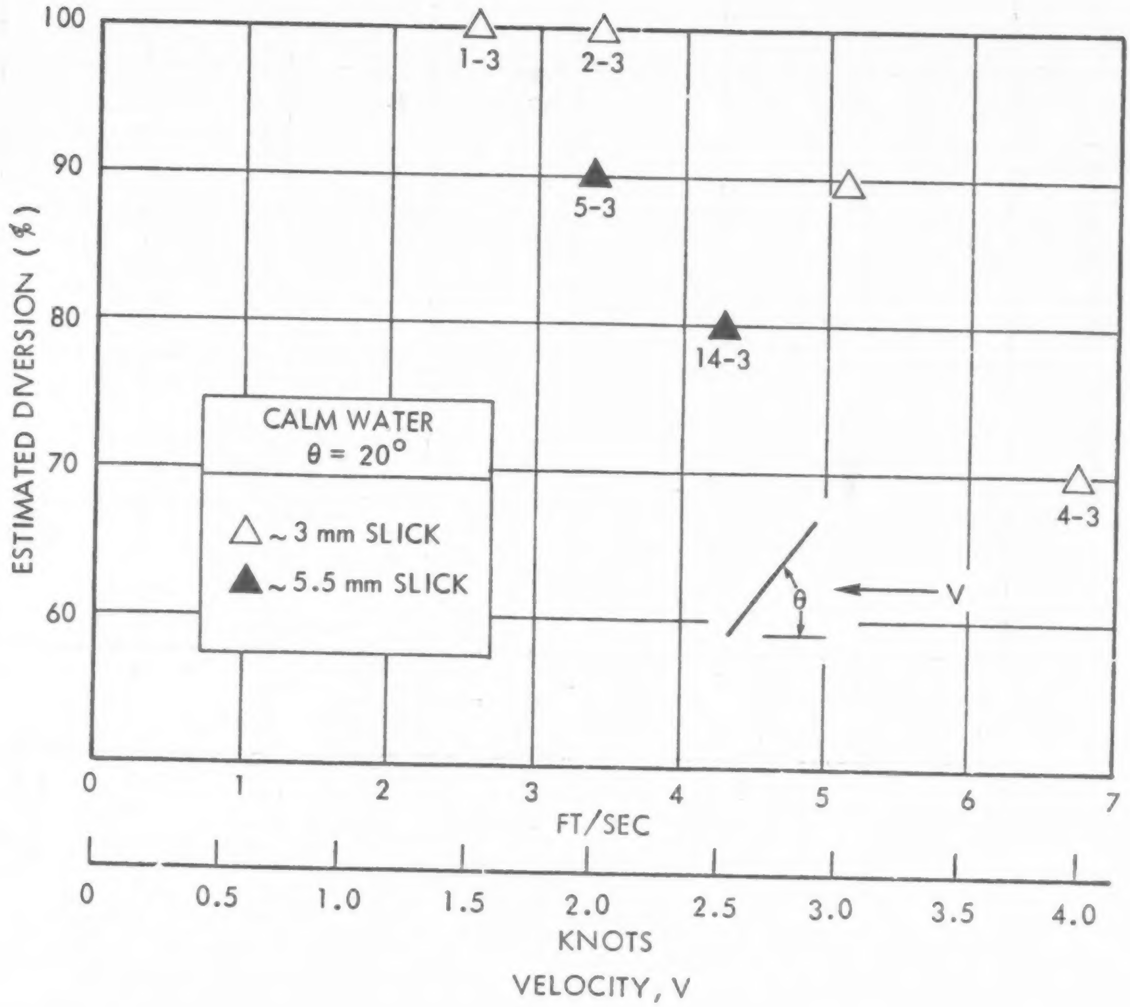

Figure 30. OHMSETT Performance Test results ($\theta = 20^0$).

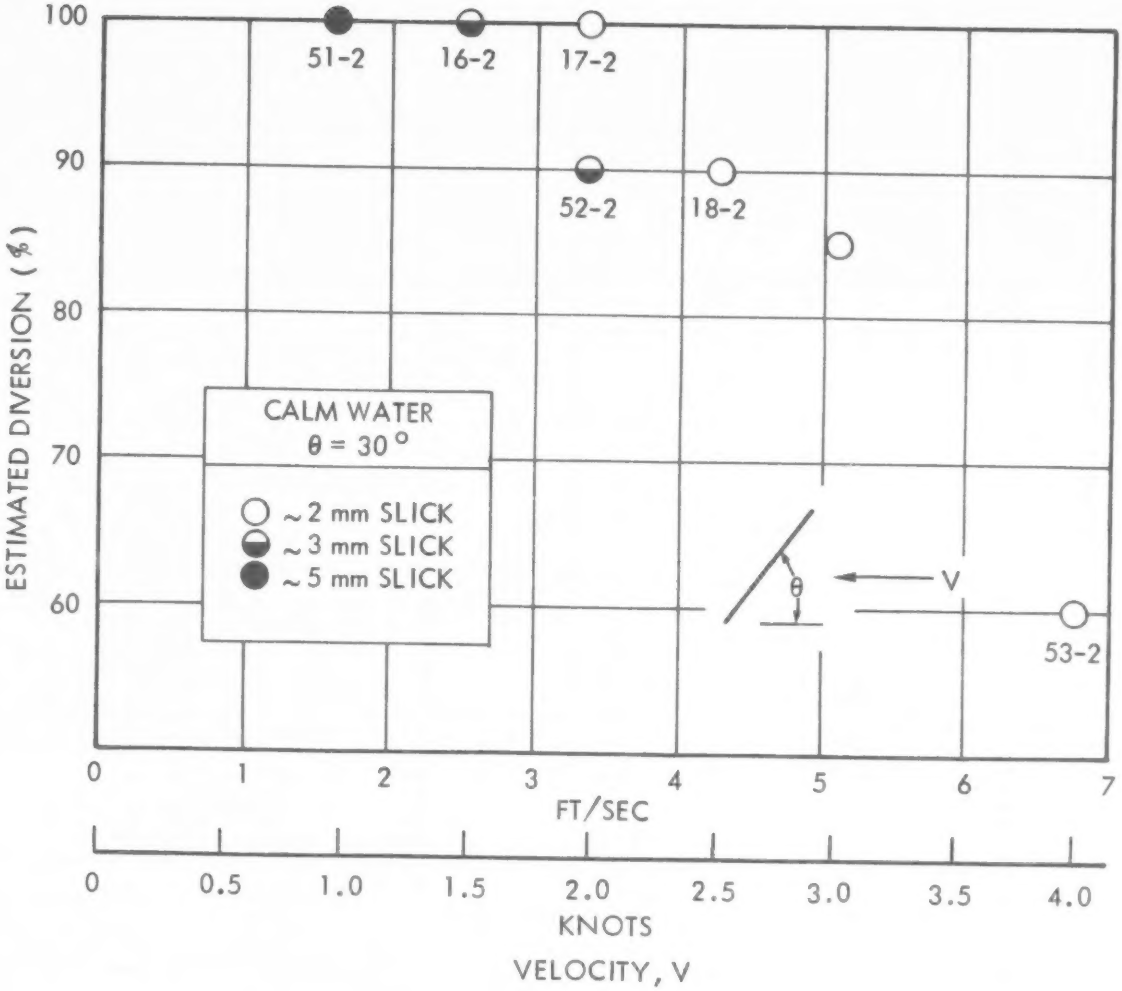

Figure 31. OHMSETT Performance Test results ($\theta = 30^0$).

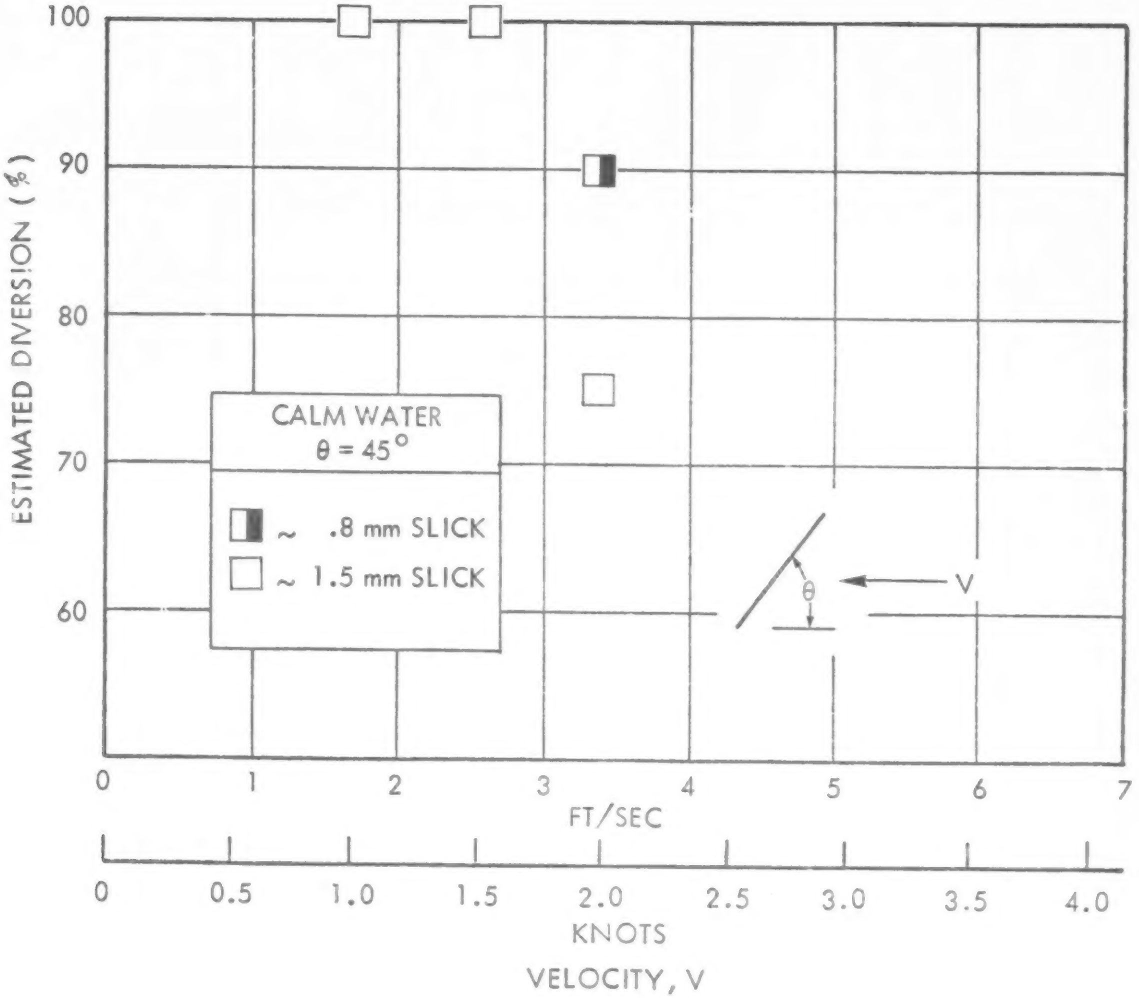

Figure 32. OHMSETT Performance Test results (θ = 45°).

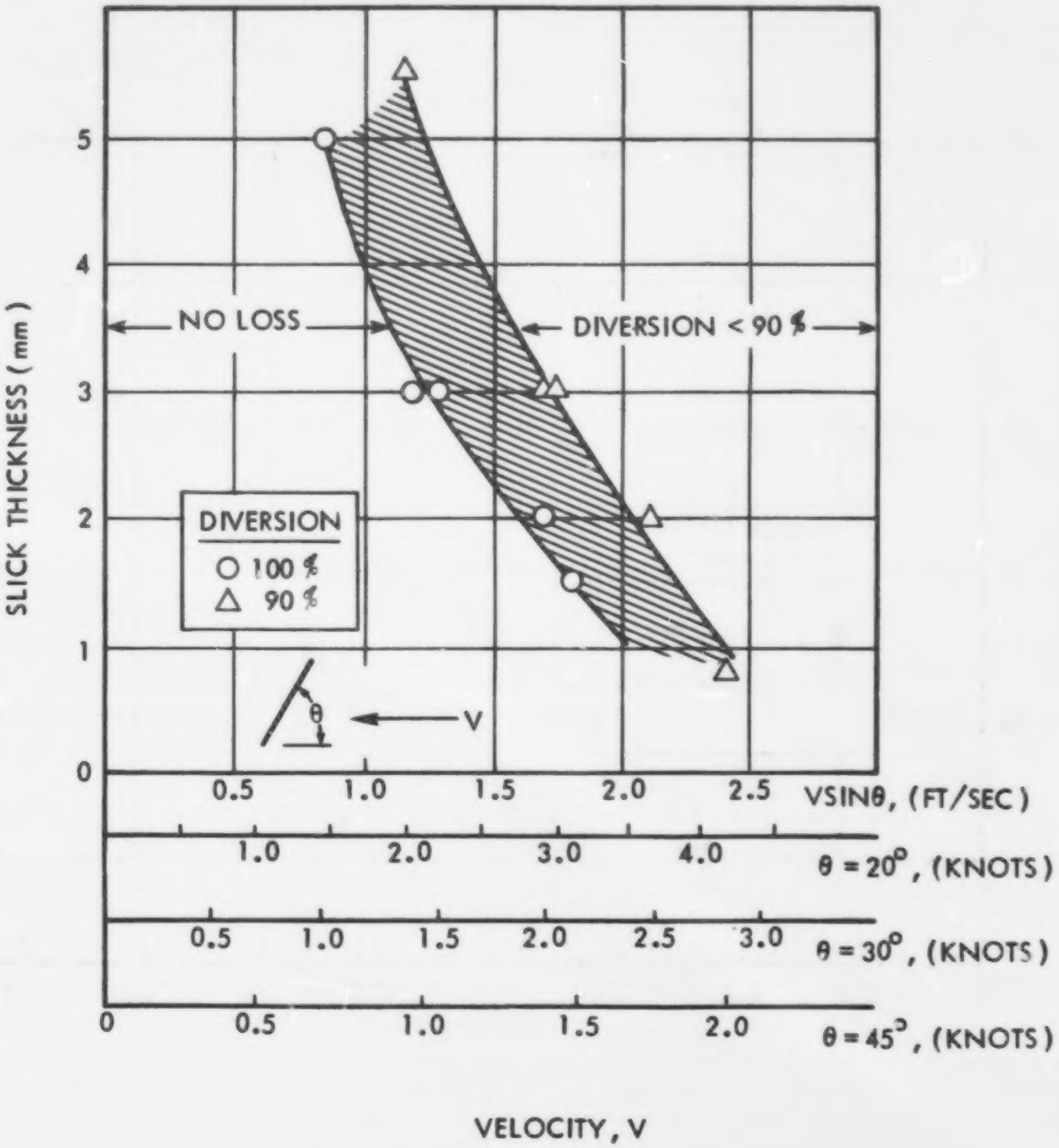

Figure 33. Summary of OHMSETT Performance Test results - calm water.

losses in waves. Another cause of increased loss is bridging of the inflatable sections over adjacent wave crests (see Figure 6b). In this case, the air jet, raised from the free surface, allows the oil slick to migrate nearer to the boom. Upon returning to the free surface, the air jet drives the oil slick (now closer to the boom) into the water column, generating oil droplets that pass beneath the boom. The light oil had a greater tendency to break up with agitation under these circumstances.

Oil loss in waves was also aggravated by structural problems. A particular problem at high speed and shallow deployment angles was for the fairing on the leading inflatable section to "dig" into approaching wave crests. The impact caused intermittent buckling, which disrupts the continuity of the air jet. This type of failure may be lessened by using a lighter weight fairing on the leading edge. A proposed design has an inflatable, all-fabric, hemispherically-shaped end piece that would eliminate the weight of the plywood end plate and Fiberglas fairing.

Reduced Power

Under certain circumstances, the air (power) supplied to the boom can be reduced without loss of performance in calm water*. For example, test results (Figure 34) show that the boom can divert 100 percent and 1 knot ($\theta = 20$ degree), using only 5 percent of the rated compressor power (Test 21-3). Similarly, at 2 knots ($\theta = 20$ degree) 100 percent can be diverted using only about 30 percent power (Test 27-3). At higher speeds, however, a power reduction will cause increased losses. For example, at 3 knots the performance drops from 90 percent (Test 3-3, 100 percent power) to 80 percent when operating at the 30 percent power level (Test 23-3).

Conditions of V, θ and t, under which power can be reduced from full power without a loss in performance, are those which fall to the left of the "no loss" curve given in Figure 33. The results of Test 21-3 demonstrates this correlation.

Savings in compressor power are made at the expense of the boom's structural characteristics, however, because of the link between the boom's strength and internal air pressure. Consequently, the inflatable section folds at lower speeds and forces restoring the section's shape are weaker. Test 25-3 (Table 5) illustrates this point. The leading inflatable section normally folds at 5 knots (full power), but folds at 3 knots when operating at the 10 percent level. Moreover, in waves, the reduced stiffness accentuates the loss in performance. For example, compare Tests 29-3 and

---

*Clearly there are numerous operational advantages for this: smaller compressors are required, fuel costs are reduced, and logistics are simplified.

34-3, shown in Figure 34. Here the influence of medium regular waves causes the diversion at the 10 percent power level to drop from 80 percent (in calm water) to 50 percent. In contrast, the effect of these waves at rated power is negligible (see Table 6).

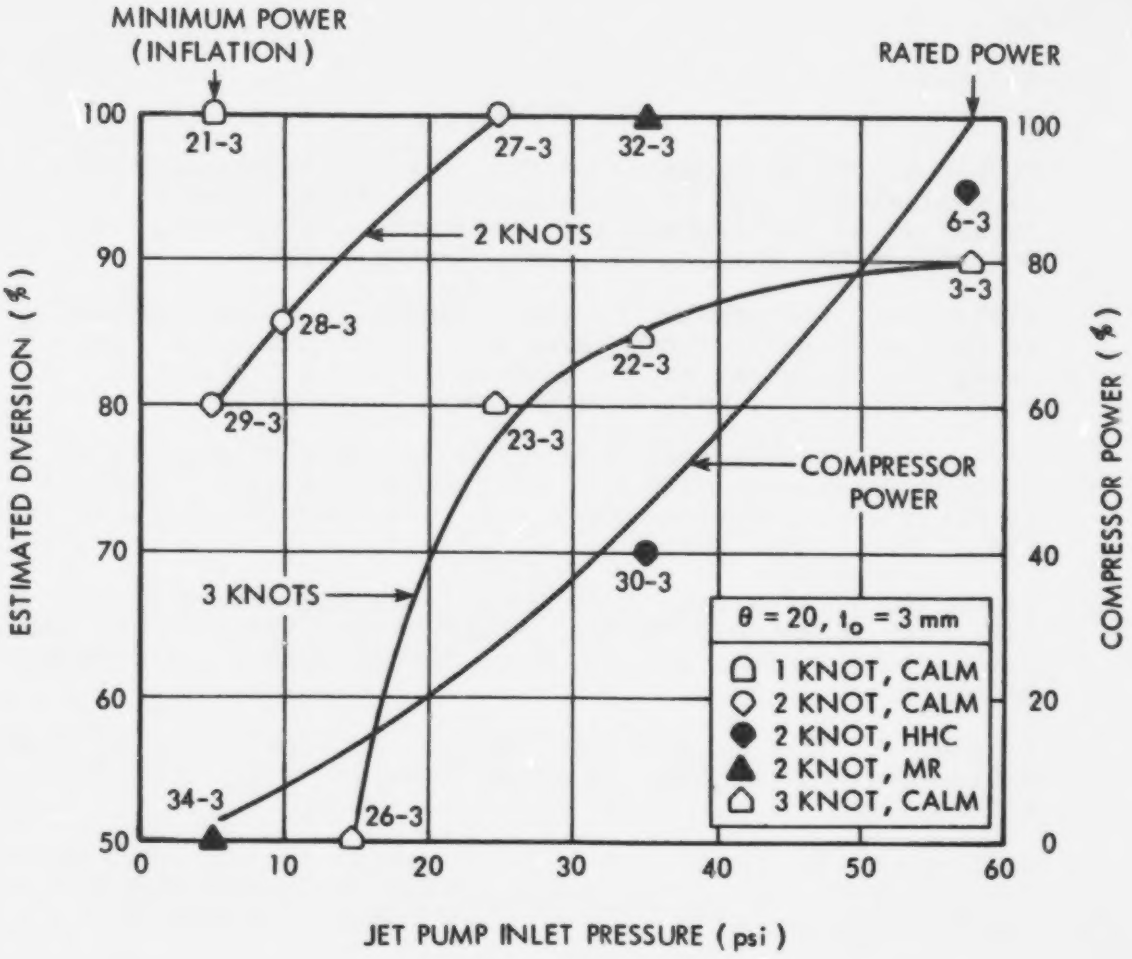

Figure 34. Effect of reduced compressor capacity on diversion performance.

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1. Wicks, M. Fluid Dynamics of Floating Oil Containment by Mechanical Barriers in the Presence of Water Currents. Presented at API-FWPCA Joint Conference on Prevention and Control of Oil Spills, New York, December 1969.

2. Miller, E., Lindenmuth, W. and Abrahams, R. Experimental Procedures Used in the Development of Oil Retention Boom Designs. Presented at The Society of Naval Architects and Marine Engineers, Marine Technology, July 1972.

3. McCracken. Performance Testing of Selected Inland Oil Spill Control Equipment. EPA-6002-77-150, August 1977 (Prepared by Mason & Hanger-Silas Mason Co., Inc. for the U. S. Environmental Protection Agency).

4. Ayers, R. R. A Rigid, Perforated Plate Oil Boom for High Currents. EPA-600/2-76-263, December 1976 (Prepared by Shell Development Company for the U. S. Environmental Protection Agency).

5. Flügel, G. The Design of Jet Pumps. National Advisory Committee for Aeronautics, Technical Memorandum No. 982, Washington, July 1941.

6. Mueller, F. N. Fast Current Oil Response System. DOT CG-D-115-75, April 1975 (Prepared by TETRADYNE CORPORATION for the U. S. Coast Guard Office of R&D) NTIS AD-A-020-171.

7. Brunner, D. E. Materials for Oil Spill Containment Boom. Technical Note N-1440, Civil Engineering Laboratory, Port Hueneme, California, NTIS-AD-A026 139, June 1976.

8. Timoshenko, S. and Young, D. H. Elements of Strength of Materials, Fifth Edition, D. Van Nostrand Company, Inc., New Jersey, 1968.

9. Baumeister, T. and Marks, L. Standard Handbook for Mechanical Engineers, Seventh Edition, McGraw-Hill, New York, 1967.

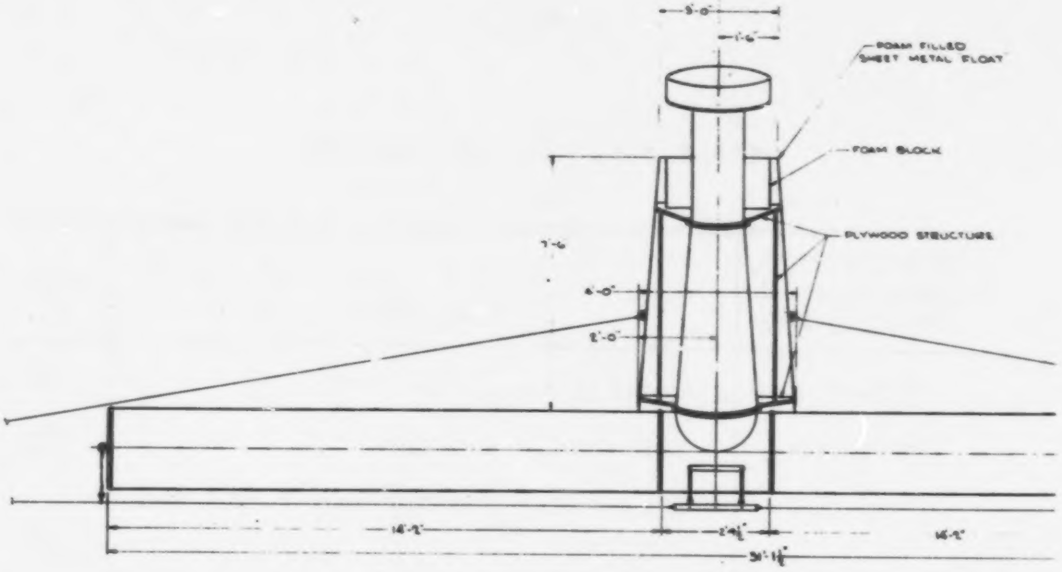
10. Hoerner, S. Fluid Dynamic Drag, published by author, 1958.

APPENDIX A

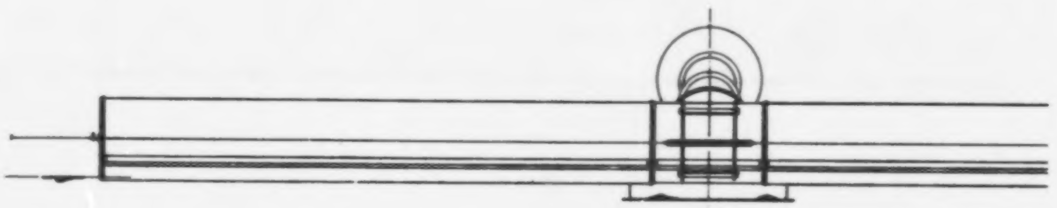
TABLE A-1. DESIGN DRAWINGS

HYDRONAUTICS, Incorporated Drawing No.	Component	Page No.
7705-001	Overall Assembly	86
7705-002	Inflatable Section	88
7705-003	Inflatable Section End Plate with Rigging	90
7705-004	Jet Pump Center Section with Rigging Turning Vanes	92
7705-005	Jet Pump Nozzle	94

DWG. NO.
7705-001


5'-0"
1'-6"
FOAM FILLED SHEET METAL FLOAT
FOAM BLOCK
PLYWOOD STRUCTURE
7'-6
4'-0"
2'-0"
14'-2"
2'-9¼"
14'-2"
31'-1¼"

PLAN VIEW



ELEVATION

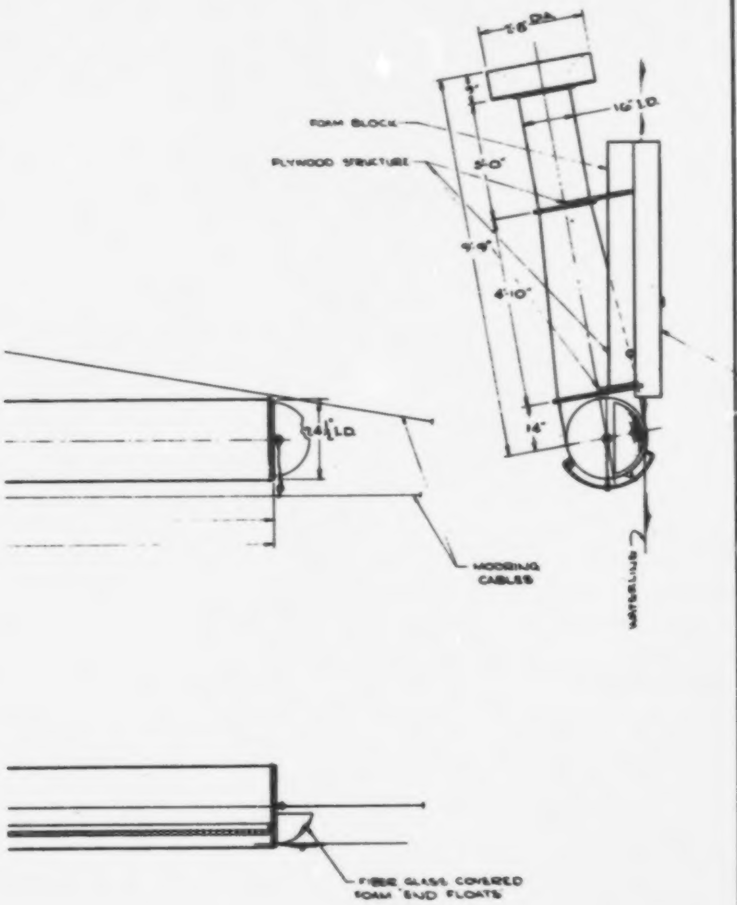
101 AIR JET OIL BOOM ASSEMBLY
ONE REQUIRED

7 6 5

A	15 DEC. 77	REDESIGNED TO 'AS-BUILT' COND	N.D.S
B	1 JUNE 78	ADDED 'AS-BUILT' FLOATS & MOORING CABLES	J.C.B.

REF. DWG'S.

7705-002	FLEXIBLE AIR DUCT DETAILS AND SUB ASS'Y
7705-003	FLEXIBLE AIR DUCT ASS'Y.
7705-004	JET PUMP ASSY


2'-6" DIA.
2"
16" I.D.
FOAM BLOCK
PLYWOOD STRUCTURE
5'-0"
9'-9"
4'-10"
14"
24" I.D.
FOAM FILLED SHEET METAL "FLOAT"
MOORING CABLES
WATERLINE
FIBER GLASS COVERED FOAM "END FLOATS"

DWG. NO. 7705-001 B

101	AIR JET OIL BOOM ASS'Y	1	

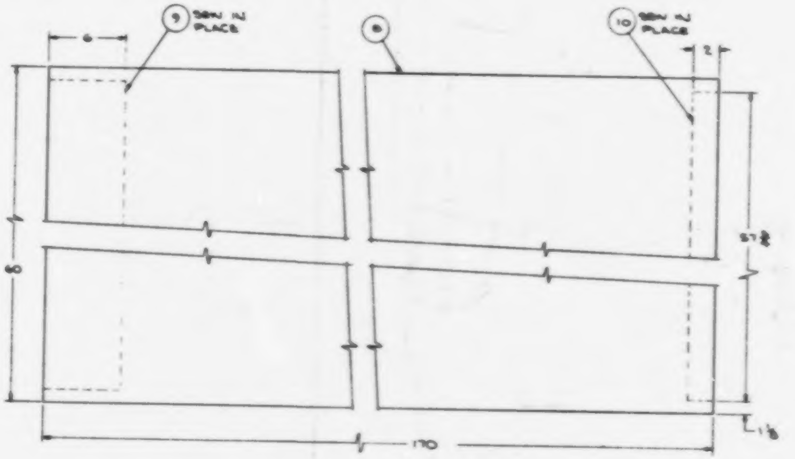
HYDRONAUTICS, INCORPORATED

AIR JET OIL BOOM
ASSEMBLY

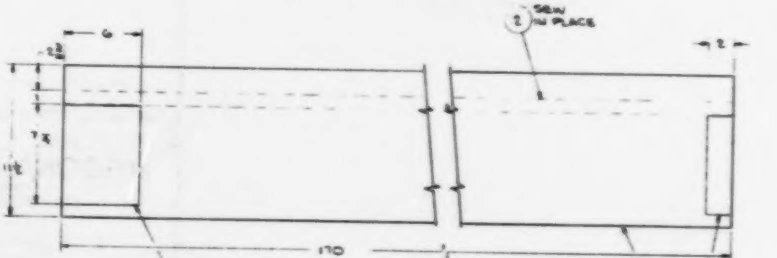
J.A. HICKEY 2-11-77
S. COHEN
7705.0242
3/4"=1'-0"
DWG. NO. 7705-001

A-2

DWG. NO.
7705-002


9 SEW IN PLACE
8
10 SEW IN PLACE
6
2
60
57 3/8
1 1/8
170

100 MID SECTION
2 REQ'D

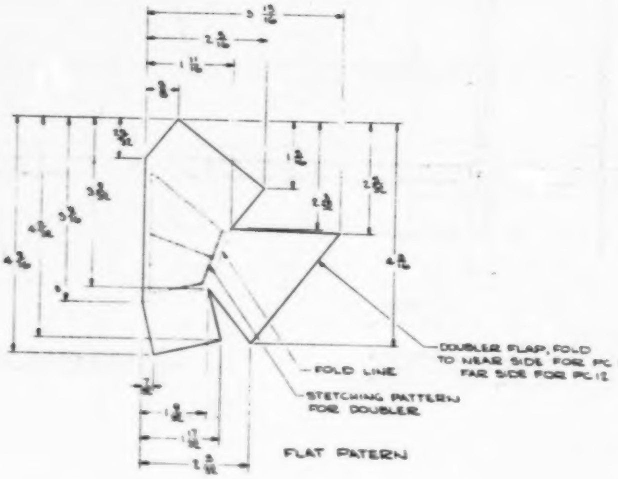

6
2 3/4
7 1/4
11 1/2
2 SEW IN PLACE
2
170
4 SEW IN PLACE
1
3 SEW IN PLACE
7
6
5

SHOWN 101 BOTTOM SECTION
1 REQ'D

OPP 102 BOTTOM SECTION
1 REQ'D

TOLERANCES, UNLESS OTHERWISE SPECIFIED

A	8 DEC 77	REDRAWN & REDESIGNED TO AS-BUILT COND	W.D.S.

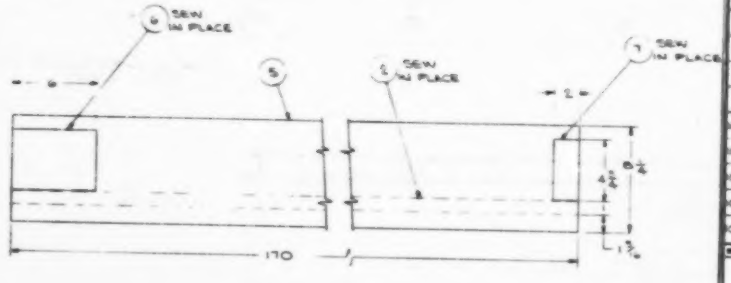


3 13/16
2 5/16
1 11/16
3/8
13/32
1 3/32
2 5/32
2 3/32
3 9/32
3 3/16
4 3/16
4 7/16
4 7/16
7/32
1 9/32
1 17/32
2 3/32
DOUBLER FLAP, FOLD TO NEAR SIDE FOR PC 11 FAR SIDE FOR PC 12
FOLD LINE
STETCHING PATTERN FOR DOUBLER

FLAT PATERN

(11) NOZZLE 85 REQ'D

(12) NOZZLE 85 REQ'D



6 SEW IN PLACE
5
2 SEW IN PLACE
7 SEW IN PLACE
6
2
8 1/4
4 3/4
1 3/16
170

SHOWN (103) TOP SECTION 1 REQ'D

OPP (104) TOP SECTION 1 REQ'D

12	FABRIC 45 MIL x 4 x 4 5/8	85	L-1030 K.E.P. (COOLEY Co)
11	FABRIC 45 MIL x 4 x 4 3/8	85	
10	FABRIC 45 MIL x 2 x 57 3/8	2	
9	FABRIC 45 MIL x 6 x 57 3/4	2	
8	FABRIC 45 MIL x 60 x 170	2	
7	FABRIC 45 MIL x 2 x 4 1/8	2	
6	FABRIC 45 MIL x 4 3/4 x 6	2	
5	FABRIC 45 MIL x 8 3/16 x 170	2	
4	FABRIC 45 MIL x 6 x 7 1/4	2	
3	FABRIC 45 MIL x 2 x 7 1/4	2	
2	FABRIC 45 MIL x 1 x 170	4	
1	FABRIC 45 MIL x 11 13/16 x 170	2	L-1030 K.E.P. (COOLEY Co)

DWG. NO. 7705-002 A

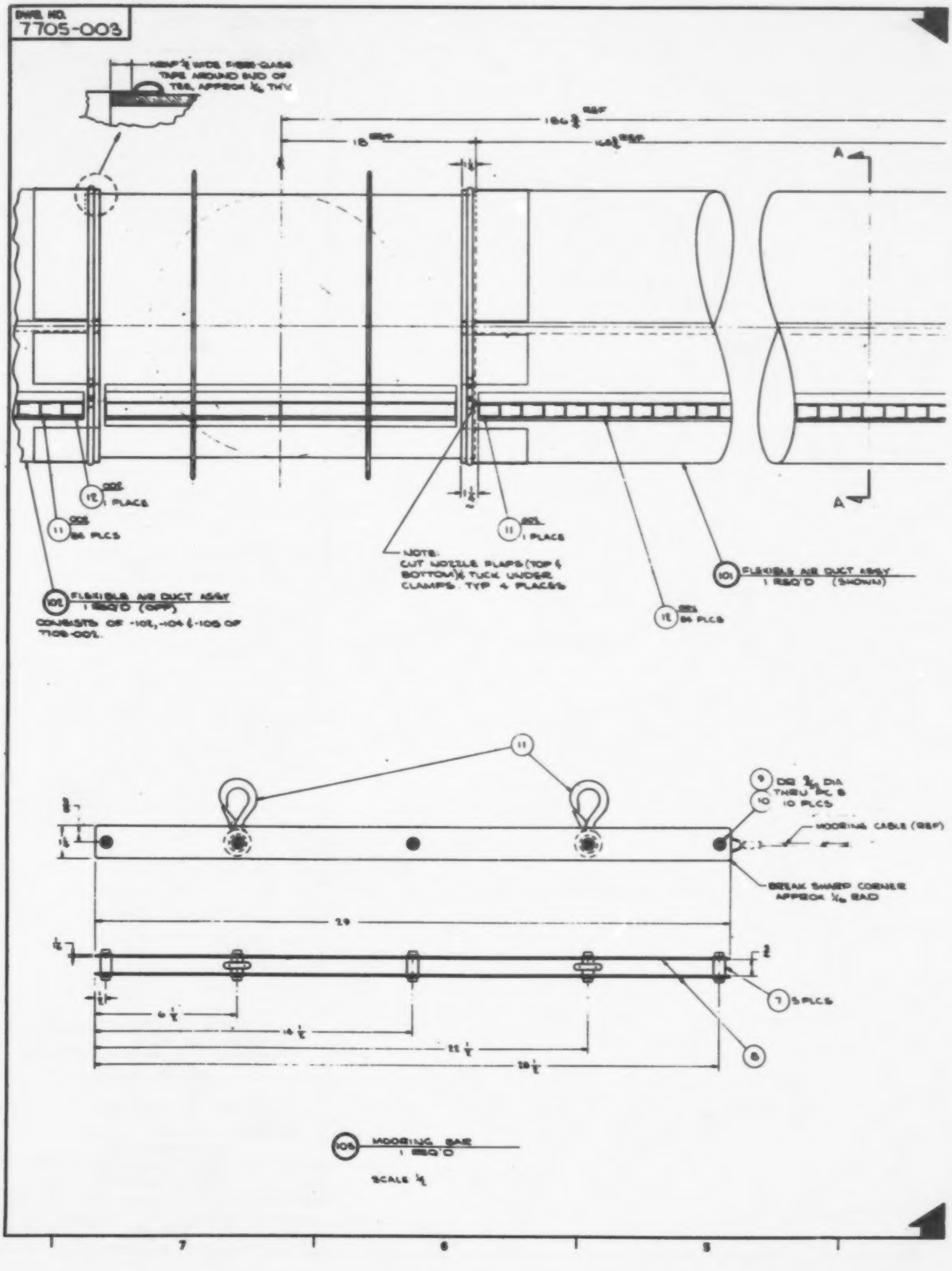
105	MID SECTION	2	
104	TOP SECTION	1	
103	TOP SECTION	1	
102	BOTTOM SECTION	1	
101	BOTTOM SECTION	1	

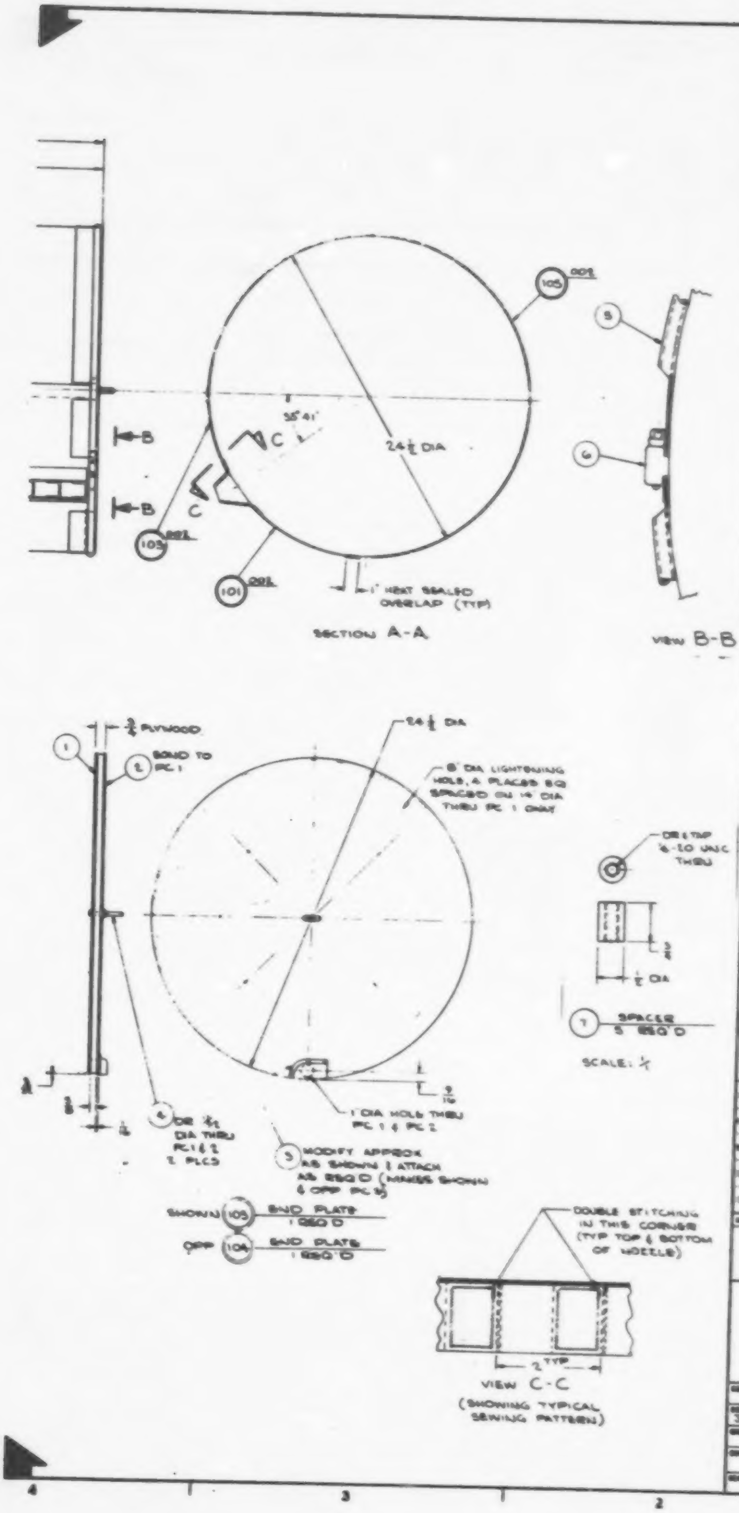
HYDRONAUTICS, INCORPORATED

AIR JET OIL BOOM

FLEXIBLE AIR DUCT DETAILS AND SUB-ASSEMBLIES

J.A. HICKEY	6-7-77	S. COHEN	
	7705.042	DWG. NO.	
1/4 & FULL		7705-002	


DWG. NO.
7705-003
WRAP ½ WIDE FIBER-GLASS TAPE AROUND END OF TEE, APPROX 1/16 THK
184 ⅜ REF
10 REF
140 REF
1/2
A
A
12 -002 1 PLACE
11 -002 84 PLCS
102 FLEXIBLE AIR DUCT ASSY 1 REQ'D (OPP)
CONSISTS OF -102, -104 & -105 OF 7705-002
1 ½
NOTE: CUT NOZZLE FLAPS (TOP & BOTTOM) & TUCK UNDER CLAMPS. TYP 4 PLACES
11 -001 1 PLACE
12 -001 84 PLCS
101 FLEXIBLE AIR DUCT ASSY 1 REQ'D (SHOWN)
11
9 DR 3/32 DIA THRU PC 8
10 10 PLCS
MOORING CABLE (REF)
BREAK SHARP CORNER APPROX 1/16 RAD
29
7 5 PLCS
8
6 ½
14 ½
22 ½
28 ½
106 MOORING BAR 1 REQ'D
SCALE ¼
7
6
5


105 003
101 003
103 003
B
B
C
C
35°41'
24½ DIA
1" HEAT SEALED OVERLAP (TYP)
SECTION A-A
5
6
VIEW B-B
1
2
⅜ PLYWOOD
BOND TO PC 1
24½ DIA
8" DIA LIGHTENING HOLE, 4 PLACES EQ SPACED ON 14 DIA THRU PC 1 ONLY
4
DR ⅛2 DIA THRU PC1 & 2 2 PLCS
1 DIA HOLE THRU PC 1 & PC 2
9/16
3
MODIFY APPROX AS SHOWN & ATTACH AS REQ'D (MAKES SHOWN & OPP PC 3)
SHOWN 105 END PLATE 1 REQ'D
OPP 104 END PLATE 1 REQ'D
DR & TAP ¼-20 UNC THRU
¾
½ DIA
7 SPACER 5 REQ'D
SCALE: ½
DOUBLE STITCHING IN THIS CORNER (TYP TOP & BOTTOM OF NOZZLE)
2 TYP
VIEW C-C
(SHOWING TYPICAL SEWING PATTERN)
4
3
2
1

A	13 DEC 77	REDRAWN & REDESIGNED TO "AS-BUILT" CONDITION	N.D.S.
B	6 June 78	ADDED MOORING BAR & DETAILS 7 THRU 11	N.D.S.

11	FAST EYE SAFETY SNAP HOOK ⅜ I.D EYE	2	BRONZE
10	¼ LOCK WASHER	10	STAIN STEEL
9	SOCK HD CAP SCREW ¼-20 UNC × ⅝ LG	10	STAIN STEEL
8	SHEET ⅛ × 1½ × 29	2	TYPE 303 STAIN STEEL
7	ROD ½ DIA × 1 LG	5	TYPE 303 STAIN STEEL
6	HOSE CLAMP ½ WIDE × 80 DIA, NORM TYPE	4	STAINLESS STEEL
5	TUBE ⅝ I.D × ⅞ OD × 74 LG	4	TYGON
4	BOW EYE PERKO FIG 237-SP	2	WM H. WHITING Co

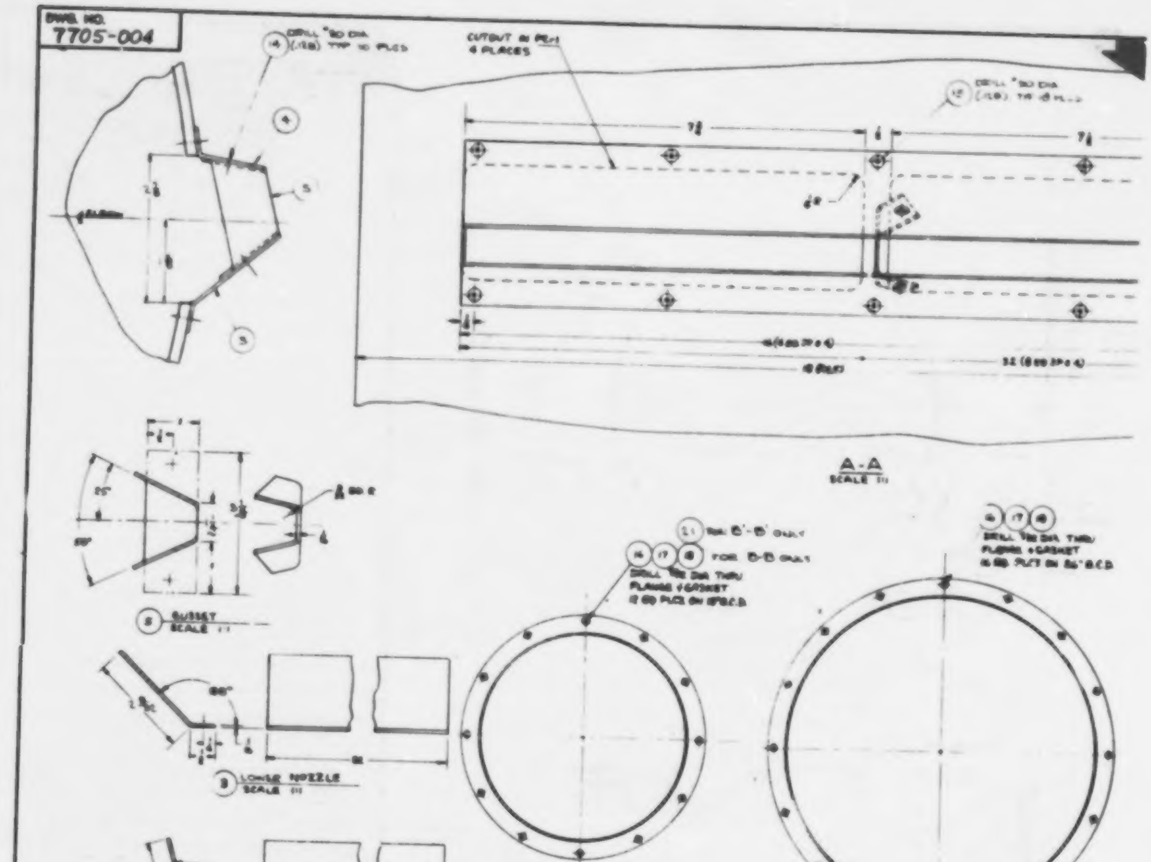
DWG. NO. 7705-003 A

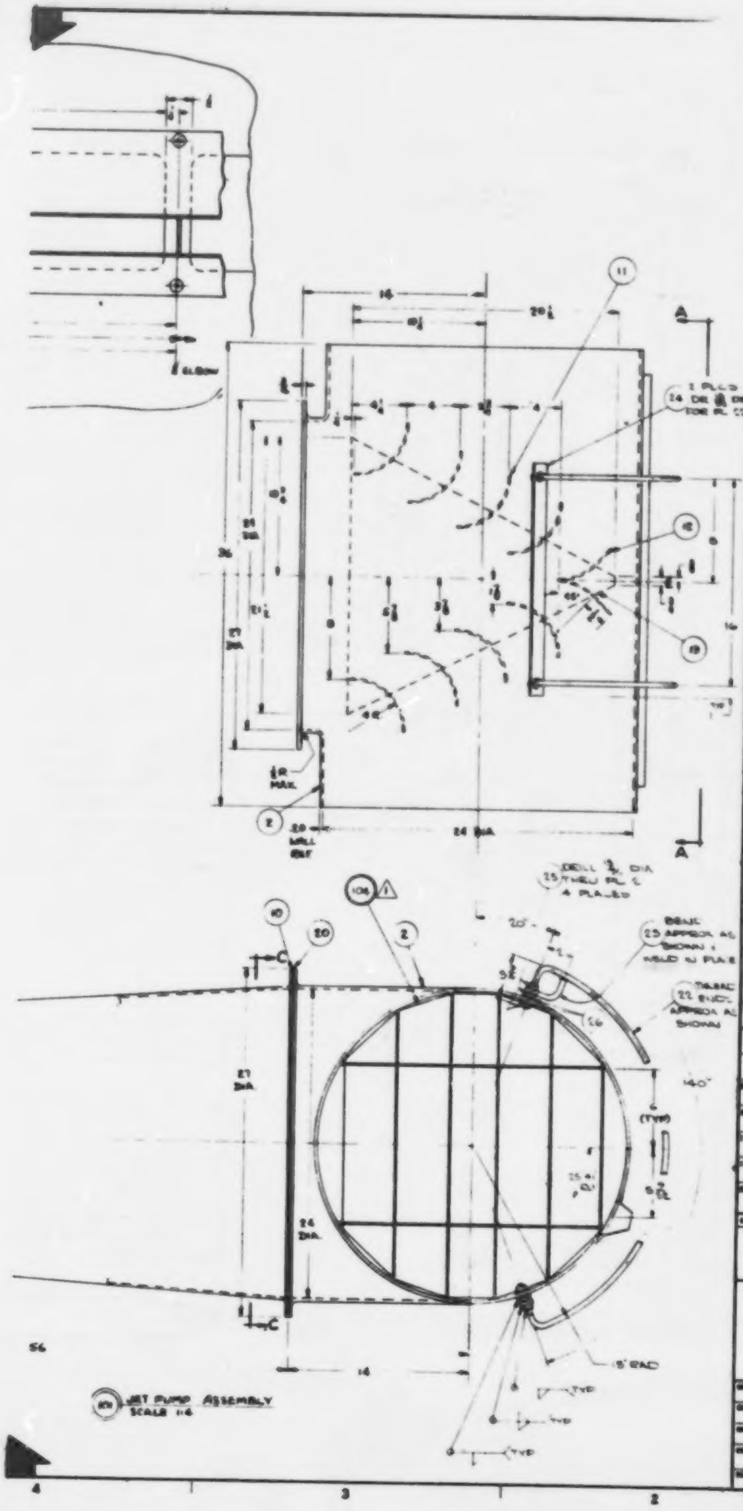
3	CLAM SHELL VENTILATOR PERKO FIG # 339-SP	1	WM H WHITING Co
2	SHEET 45 MIL × 25 × 25	2	L-1030 K E P COOLEY Co
1	PLYWOOD ⅜ × 25 × 25	2	MARINE FIR AB
102	MOORING BAR	1	
104	END PLATE	1	
103	END PLATE	1	
102	FLEXIBLE AIR DUCT ASSY	1	
101	FLEXIBLE AIR DUCT ASSY	1	

HYDRONAUTICS, INCORPORATED

AIR JET OIL BOOM
FLEXIBLE AIR DUCT ASSEMBLY

J.A. HICKEY	2-9-77	S. COHEN	
	7705.0242	DWG. NO. 7705-003	
½ & FULL			


DWG. NO.
7705-004
DRILL .130 DIA (.128) TYP 10 PLCS
CUTOUT IN PE-1 4 PLACES
A-A
SCALE 1:1
GUSSET
SCALE 1:1
LOWER NOZZLE
SCALE 1:1
UPPER NOZZLE
SCALE 1:1
FOR B'-B' ONLY
FOR B-B ONLY
DRILL DIA THRU FLANGE + GASKET
B-B
B'-B'
C-C
COAT WITH EVERFIL
FIBERGLASS
B'
B
7
6
5



11
A
16
10 1/4
20 1/2
2 PLCS
24 DR & DR FOR PL 22
18
19
16
36
27 DIA
24 DIA
2
20 WALL REF
1/8 R MAX
ELBOW
10
20
104 ⚠1
2
25 DRILL 1/8 DIA THRU PL 5 4 PLACES
20°
23 BEND APPROX AS SHOWN & WELD IN PLACE
22 THREAD ENDS APPROX AS SHOWN
26
140°
(TYP)
27 DIA
24 DIA
14
15' RAD
TYP
C
56
101 JET PUMP ASSEMBLY SCALE 1:6
4
3
2

A	15 OCT 77	REVISED NOZZLE LOCATION & BELLMOUTH CONSTRUCTION ADD MOORING RINGS, PLS 22 THRU 26	W.D.C.

Note ⚠1 SOFT SOLDER ASSEMBLY

⚠2 FLARE 1/4 MIN. FLANGE ON EACH END OF DUCT & SOLDER FLANGE IN PLACE

⚠3 MATCH MARK ASSEMBLIES

26	FLAT WASHER 3/8	8	STAINLESS STEEL
25	HEX NUT 3/8-16 UNC	12	STAINLESS STEEL
24	BAR 1/4 x 1 x 18	2	304 STAINLESS STEEL
23	ROD 3/8 DIA x 4	2	304 STAINLESS STEEL
22	ROD 3/8 DIA x 48	2	304 STAINLESS STEEL
21	WOOD SCREW #12 x 1 1/2 ROUND HEAD	16	STAINLESS STEEL
20	GASKET 1/4 x 27 x 27	1	NEOPRENE 50 SHORE
19	GASKET 1/8 x 19 x 19	2	NEOPRENE 50 SHORE
18	LOCK WASHER #10	96	18-8 CORR. STEEL
17	NUT #10-24NC	96	18-8 CORR. STEEL
16	SCREW #10-24NC x [illegible]	96	18-8 CORR. STEEL
15	POP RIVET - 1/8 DIA. ALUM. AD(42)ABS	18	USM FASTENER CO.
14	POP RIVET - 1/8 DIA. ALUM AD(62)ABS	10	USM FASTENER CO
13	PLATE 16 GAGE (063) 20 1/2 x 21 1/2	2	GALV STEEL
12	VANE 20 GAGE (031) x 6 x 20 1/2	2	
11	VANE 20 GAGE (031) x 7 x 23 1/2	8	
10	FLANGE 16 GAGE (063) x 27 x 27	1	
9	TRANSITION - LOCK SEAM 20 GAGE (031) x 80 x 64	1	
8	FLANGE 16 GAGE (063) x 19 x 19	2	
7	DUCT - LOCK SEAM 20 GAGE (031) x 40 x 27	1	GALV STEEL
6	GUSSET 1/16 x 1 x 2 3/4	8	6061-T6 ALUM
5	GUSSET 1/16 x 1 x 3 1/4	8	6061-T6 ALUM

DWG. NO. 7705-004 A

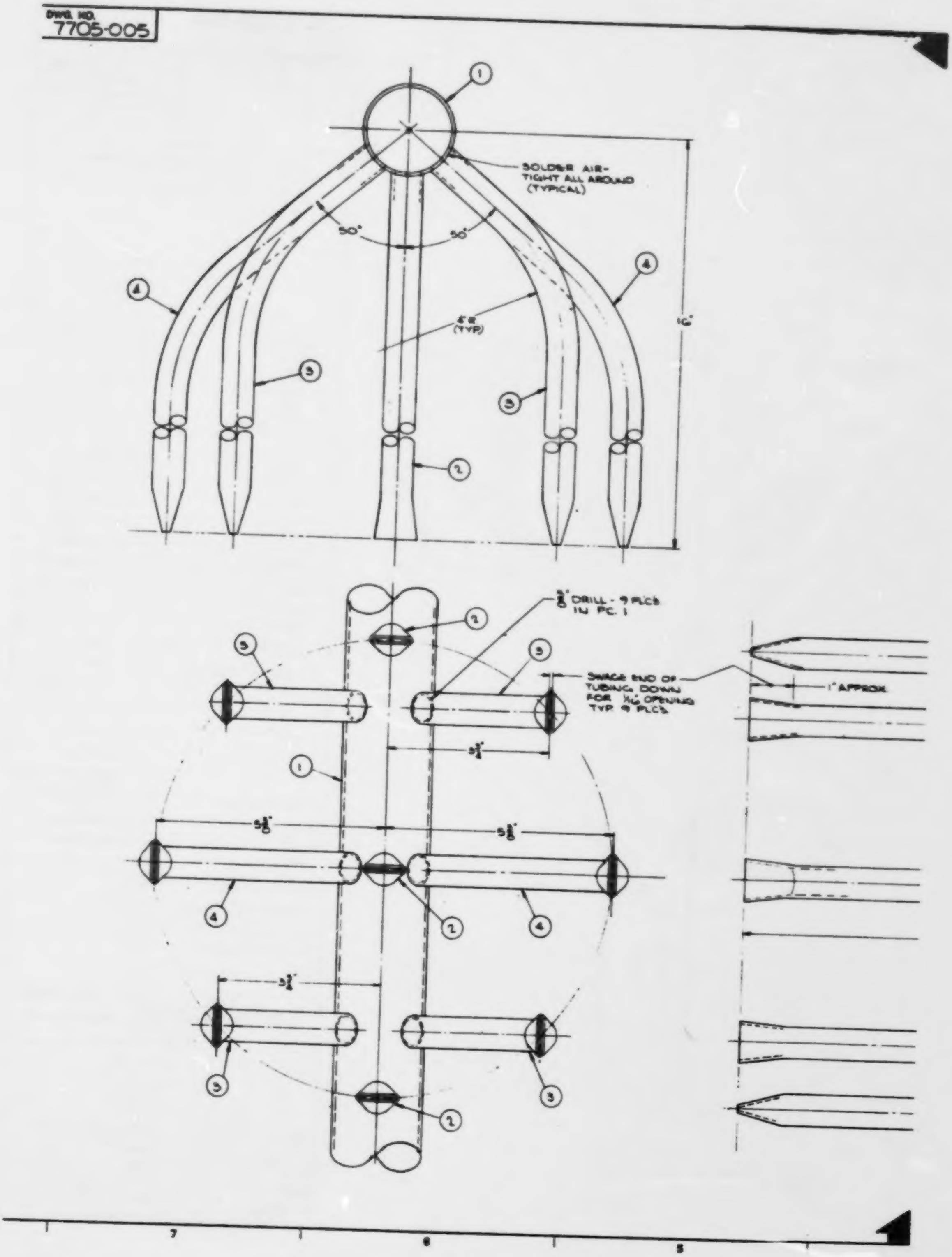
4	UPPER NOZZLE 1/16 x 2 x 32	1	6061-T6 ALUM
3	LOWER NOZZLE 1/16 x 3 x 32	1	6061-T6 ALUM
2	ELBOW - FIBERGLASS 24 I.D.	1	JONES & HUNT
1	PLYWOOD 3/4 x 36 x 36	1	MARINE FIR AC
105	NOZZLE ASSEMBLY	1	
104	TURNING VANE ASSEMBLY	1	
103	DIFFUSER ASSEMBLY	1	
102	INLET ASSEMBLY	1	
101	JET PUMP ASSEMBLY	1	

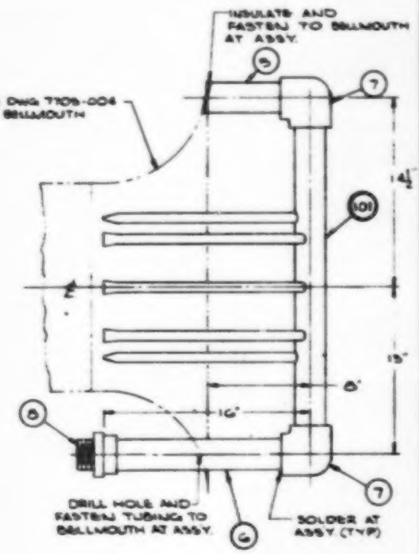
HYDRONAUTICS, INCORPORATED

AIR JET OIL BOOM
JET PUMP
DETAIL & ASSEMBLY

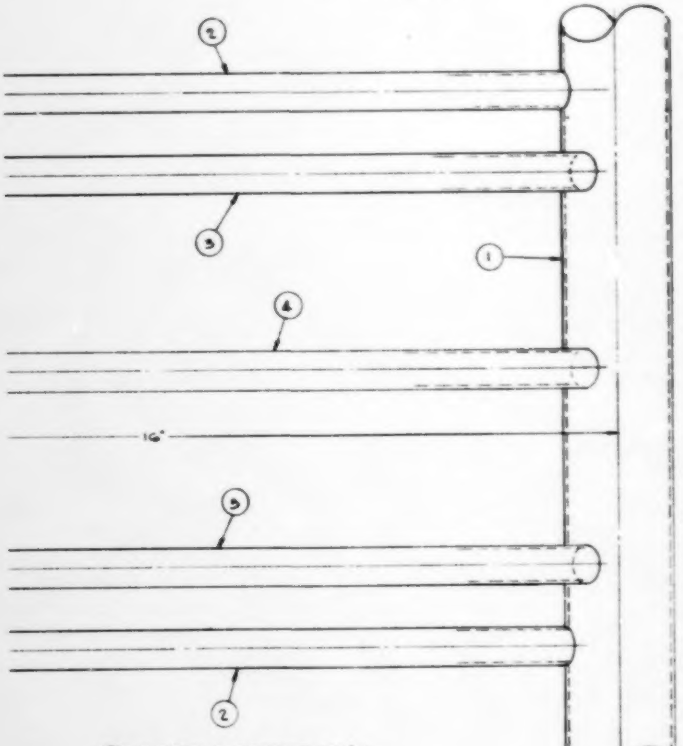
		S. COHEN	
H. HICKEY	2-11-77		
	7705.0242	DWG. NO. 7705-004	
AS NOTED			

93


DWG. NO.
7705-005
①
SOLDER AIR-TIGHT ALL AROUND (TYPICAL)
50°
50°
④
④
6" R (TYP)
16"
③
③
②
3/8" DRILL - 9 PLCS. IN PC. 1
②
③
③
SWAGE END OF TUBING DOWN FOR 1/16 OPENING TYP. 9 PLCS.
1" APPROX.
5 3/4"
①
5 5/8"
5 5/8"
④
②
④
5 3/4"
③
③
②
7
6
5


INSULATE AND FASTEN TO BELLMOUTH AT ASSY.
SEE DWG 7705-004 FOR BELLMOUTH
5
7
101
4 1/2"
15"
8"
16"
8
DRILL HOLE AND FASTEN TUBING TO BELLMOUTH AT ASSY.
6
7
SOLDER AT ASSY (TYP)

DETAIL 1
NOZZLE TO BELLMOUTH ASSY
SCALE 1:4



(101) NOZZLE SPIDER ASSY
ONE REQUIRED

8	ADAPTER 2" TUBE x MALE I.P. THRD	1	COPPER
7	2" STD ELBOW	2	COPPER
6	TUBING 2 1/8" O.D. x 2" I.D. x 16" LG	1	TYPE "L" COPPER
5	TUBING 2 1/8" OD x 2" ID x 8" LG	1	
4	TUBING 3/4" O.D. x 5/8" I.D. x 17 1/2" LG	2	
3	TUBING 3/4" O.D. x 5/8" I.D. x 16 1/2" LG	4	
2	TUBING 3/4" OD x 5/8" ID x 15 1/2" LG	3	
1	TUBING 2 1/8" OD x 2" ID x 38" LG	1	TYPE "L" COPPER
101	NOZZLE SPIDER ASSY	1	

DWG. NO. 7705-005

HYDRONAUTICS, INCORPORATED

AIR JET OIL BOOM
NOZZLE SPIDER

		S COHEN	
J A HICKEY	2-15-77		
	7705.0242	DWG. NO. 7705-005	
FULL			

APPENDIX B

EPA DESIGN GUIDELINES

Guidelines for the design of the Air-Jet Boom were outlined in Request for Proposal CI-76-0136, solicited by the U. S. Environmental Protection Agency during April 1976. In part, they were established, based on the work of Mueller (Reference 6) who used air jets for similar purposes.

Because these guidelines provide a foundation for this work, they are given below:

(1) The boom shall be approximately 33 feet in length, 2 feet in diameter and have a cross section approximately of that in Figure B-1.

(2) The material of construction shall be fabric reinforced plastic which is capable of being fastened together by simple means, using heat seal or equivalent technology.

(3) For strength purposes, the boom shall be designed to survive in a 10-knot river and operate effectively in a 6-knot current with debris.

(4) The flexible, metal, ballast/tension member shall be either chain or cable, suitably coated to permit use in fresh, brackish or seawater, and enclosed in a fabric sleeve. It shall be located so as to help counteract the reaction of the jet. Figure B-1 shows the approximate location.

(5) The air required for inflation and for the air jet shall be supplied by commercial grade, gasoline or diesel powered air compressors of the sort commonly available for tent.

(6) The high-pressure, low-volume-air output from these compressors shall be led by means of flexible hoses to one or more venturi nozzles attached directly to the boom section. The nozzles shall supply low-pressure, high-volume air to each boom section. At least 15,000 cubic feet per minute at 3.25 inches water pressure will be required.

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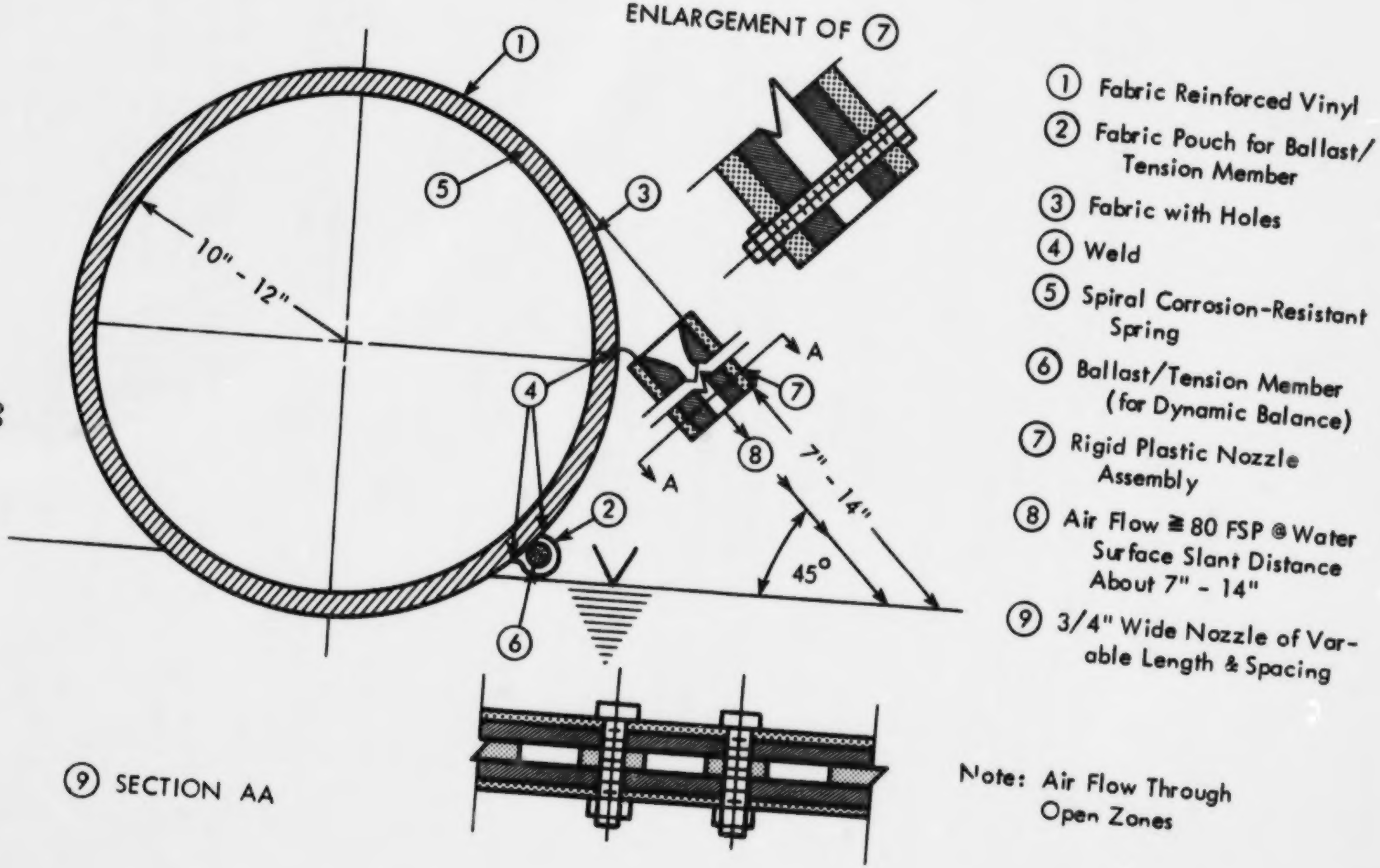

ENLARGEMENT OF ⑦
①
⑤
③
10" - 12"
④
⑦
⑧
A
A
②
⑥
7" - 14"
45°
⑨ SECTION AA
① Fabric Reinforced Vinyl
② Fabric Pouch for Ballast/ Tension Member
③ Fabric with Holes
④ Weld
⑤ Spiral Corrosion-Resistant Spring
⑥ Ballast/Tension Member (for Dynamic Balance)
⑦ Rigid Plastic Nozzle Assembly
⑧ Air Flow ≧ 80 FSP @ Water Surface Slant Distance About 7" - 14"
⑨ 3/4" Wide Nozzle of Variable Length & Spacing
Note: Air Flow Through Open Zones

Figure B-1. Proposed EPA Air Jet Boom cross section.

(7) The rectangular air-jet nozzles shall be 3/4-inch wide and of variable length and spacing, as needed to produce the required velocity distribution a) within the boom, b) from the nozzles, and c) at the water surface (at least 80 feet per second is required at the latter location). The axis of the nozzle shall make an angle of 45 degrees with the water surface, and the slant distance shall be 7 to 14 inches (Figure B-1) under typical wave conditions.

(8) Prior to starting the compressor, or in the event that it should fail, the boom shall float when deployed and shall easily support the associated hoses, nozzles, attached mooring apparatus and any other appurtenances. For example, a light, internal spiral spring could be used to prevent collapse in the event of loss of air pressure.

(9) The design shall be easily deployed, deoiled, stored and capable of interconnection with conventional booms.

(10) The boom configuration shall be clean and simple.

(11) The boom and its supporting equipment shall be highway transportable by a 3/4-ton pickup truck.

(12) The boom and its supporting equipment shall be designed to have the capability of operating continuously without a breakdown for 14 days.

APPENDIX C

FABRIC SELECTION

The suitability of various fabric materials for use in the construction of oil booms was considered by Brunner (Reference 7). It was found that fabrics acceptable for this service are, in general, composed of a woven substrate and a natural or synthetic elastomer coating. The woven substrate usually accounts for mechanical properties (e.g., strength of the fabric), while the coating characterizes the physical and chemical properties. For the present application, the following properties were considered an important criteria in substrate and coating selections:

Break strength	(Substrate)
Tear strength	(Substrate)
Creep resistance	(Substrate)
Flexibility	(Coating)
Puncture resistance	(Coating)
Abrasion resistance	(Coating)
Chemical and Petroleum Resistance	(Coating)
Repairability	(Coating)
Heat sealing ability	(Coating)

Samples conforming to these criteria and capable of withstanding estimated loads (Appendix D) with an adequate factor of safety were acquired from six major manufacturers. After screening the samples and considering recommendations in Reference 7, a polyester substrate with a urethane coating was selected. The physical properties are as follows:

Tensile strength	135 pound/inch (warp)[*]
	160 pound/inch (fill)[†]
Tear strength	440 pound/inch (warp)
	330 pound/inch (fill)

---

[*] Refers to the direction along the length of the fabric.

[†] Refers to the direction across the width of the fabric (selvage to selvage, typically 60 inches).

Preceding page blank

Thickness, total	.030 inches
Weight, total	30 ounces/yard^2
Weight, substrate	5.5 ounces/yard ^{2}
Fiber	2,000 denier[†] (fill)
	1,000 denier (warp)

Tests of the heat-sealed joint efficiency were conducted for 1-inch lap joints. Results, based on three specimens, were that the joints were 100 percent efficient and failure occurred in the substrate without rupturing the coating. Long-term creep tests of the fabric are given in Figure C-1.

[†] Refers to the weight in grams of a 9,000 meter length (i.e., a measure of cross-sectional area).

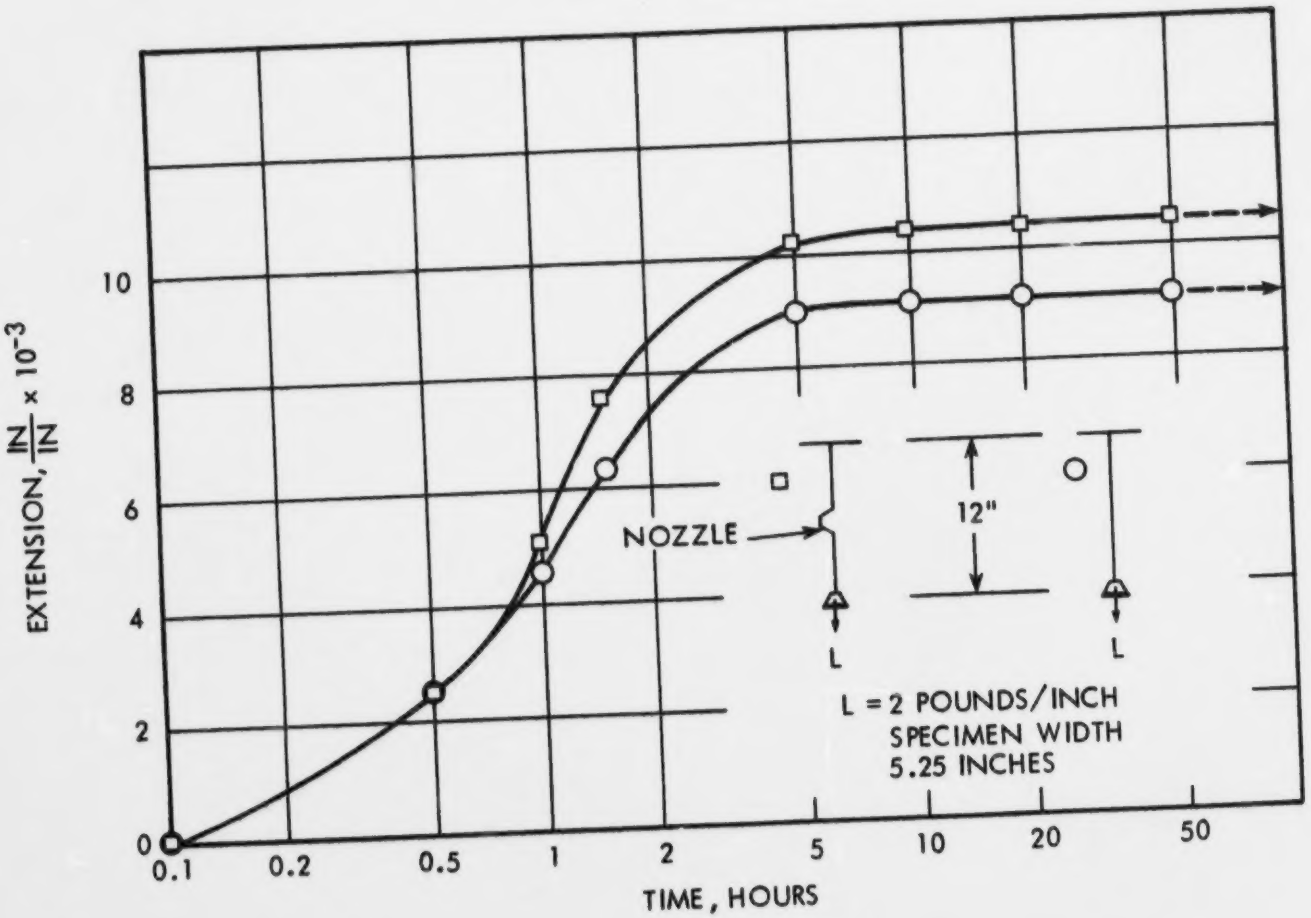


Figure C-1. Dead load creep tests. (Summary of results).

APPENDIX D

STRUCTURAL ANALYSIS OF THE INFLATABLE SECTIONS

STRUCTURAL STABILITY

Assuming the inflatable section is thin (weightless) and supported by internal air pressure with no external loads, the membrane stresses are uniformly distributed in the axial circumferential directions and calculated from the equations:

$$\sigma_{a_o} = \frac{c\ pr}{2f} \qquad [1]$$

and

$$\sigma_{c_o} = \frac{c\ pr}{f} \qquad [2]$$

where

σ_{a_o} = axial stress due to air pressure, pounds/inch^2

σ_{c_o} = circumferential stress due to air pressure, pounds/inch^2

p = internal air pressure, inches of water

r = radius of the inflatable sections, 12 inches

c = conversion, .036 psi/inch of water

f = fabric thickness, .030 inches (see Appendix C)

The resulting strain causes the inflatable section to increase in length and diameter.

With external loads acting (e.g., weight, drag, etc.), the distribution of stress and strain will become nonuniform causing lateral and/or torsional deflections of the inflatable section. These stresses can be calculated by using linear beam theory and the principle of superposition (Reference 8) where the net stress is due to the algebraic sum of the stress due to air pressure and the stress due to external load. As long as the net membrane stresses are positive (tensile) at each point on the fabric, the theory is valid. However, if the net stress should become negative (compressive), the inflatable section can become unstable

Preceding page blank

or buckle since the fabric cannot support compression. Therefore, the criterion used for structural stability is that the membrane stress must always be greater or equal to zero.

Several conditions of loading are considered below:

Case One

Inflatable section floating with uniformly distributed horizontal load-cantilever support (see Figure D-1).

From the linear beam theory, the stress due to uniform load on a cantilevered beam is calculated by the equation:

$$\sigma_{a_1} = \pm \frac{\omega \ell_1{}^2 r}{2I} \qquad [3]$$

where

σ_{a_1} = axial stress due to horizontal load, pounds/inch^2

ω = uniform horizontal load, pounds/inch

ℓ_1 = length of the inflatable section, 165 inches

r = radius of the inflatable section, 12 inches

I = moment of inertia, 244 inches^4

(Note: σ_{c_1} is zero for small deflections)

Superimposing the axial stress, due to internal air pressure, (Equation 1), the minimum and maximum membrane stresses (at the locations indicated in Figure D-1) are then:

$$\sigma_{a_{min}} = \frac{c\ pr}{2f} - \frac{\omega \ell_1{}^2 r}{2I} \qquad [4]$$

and

$$\sigma_{a_{max}} = \frac{c\ pr}{2f} - \frac{\omega \ell_1{}^2 r}{2I} \quad . \qquad [5]$$

but since

$$\sigma_{a_{min}} \geq 0 \text{ (stability criteria)} \quad , \qquad [6]$$

the maximum uniform horizontal load, which can be supported without loss of structural stability (ω_s), is (determined by combining equations 4 and 6):

$$\omega_s \leq \left(\frac{cI}{f\ell_1{}^2}\right) p \qquad [7]$$

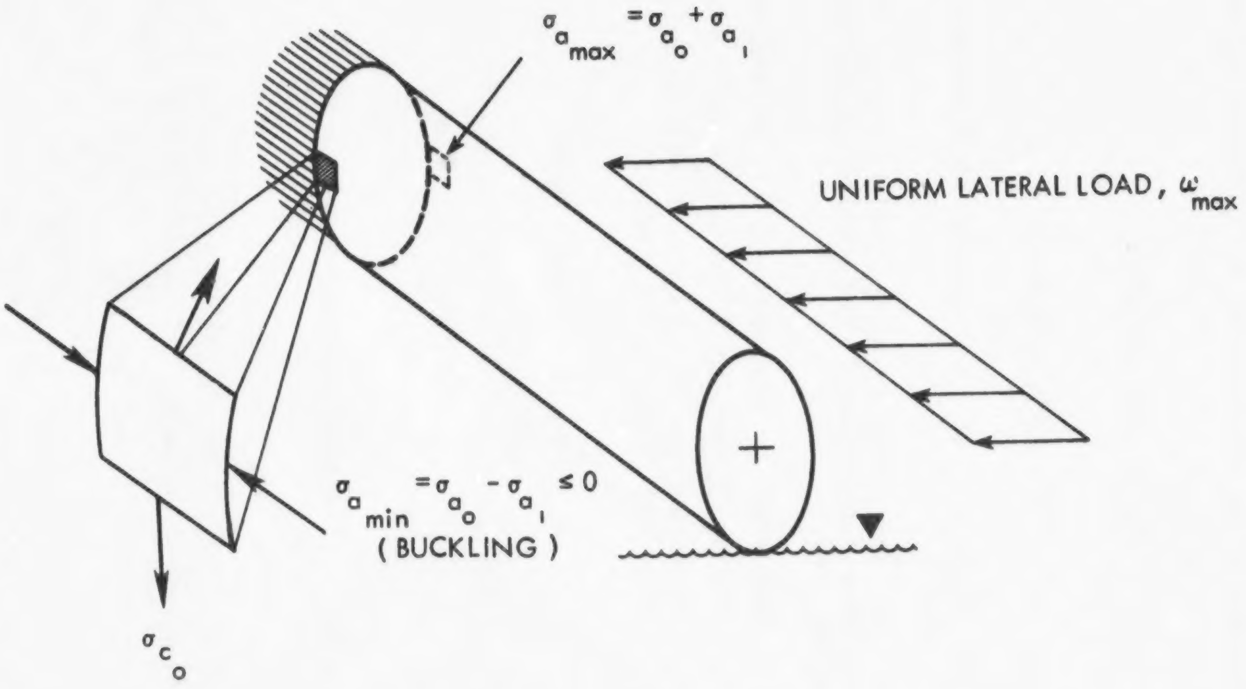

$\sigma_{a_{max}} = \sigma_{a_o} + \sigma_{a_1}$
UNIFORM LATERAL LOAD, ω_{max}
$\sigma_{a_{min}} = \sigma_{a_o} - \sigma_{a_1} \leq 0$
(BUCKLING)
σ_{c_o}

Figure D-1. Inflatable section under uniformly distributed horizontal load - cantilever support.

or

$$\leq (1.1 \times 10^{-2})\, p \quad . \qquad [8]$$

Further, if the design air pressure, 3.25 inches of water, is assumed

$$\omega_s \leq .036 \text{ pound/in.} \qquad [9]$$

or

$$\leq .430 \text{ pound/ft} \quad . \qquad [10]$$

Hence loads in excess of .430 pounds/ft delineate the threshold of buckling (folding).

Using the load estimates from Appendix D, page 106, a maximum value of ω was obtained. The following assumptions (worst case) were used:

(1) The boom is deployed at $\theta = 90$ degrees

(2) The tow speed is V = 6 knots (~10 feet/second)

(3) Loads are due to drag and nozzle reactions ($\ell = 3/4''$ and $\alpha = 45$ degrees)

so that

$$\omega_{max} = 1.85 \text{ pounds/foot} \quad . \qquad [11]$$

By comparing with Equation 10,

$$\omega_{max} \gg \omega_s \; , \qquad [12]$$

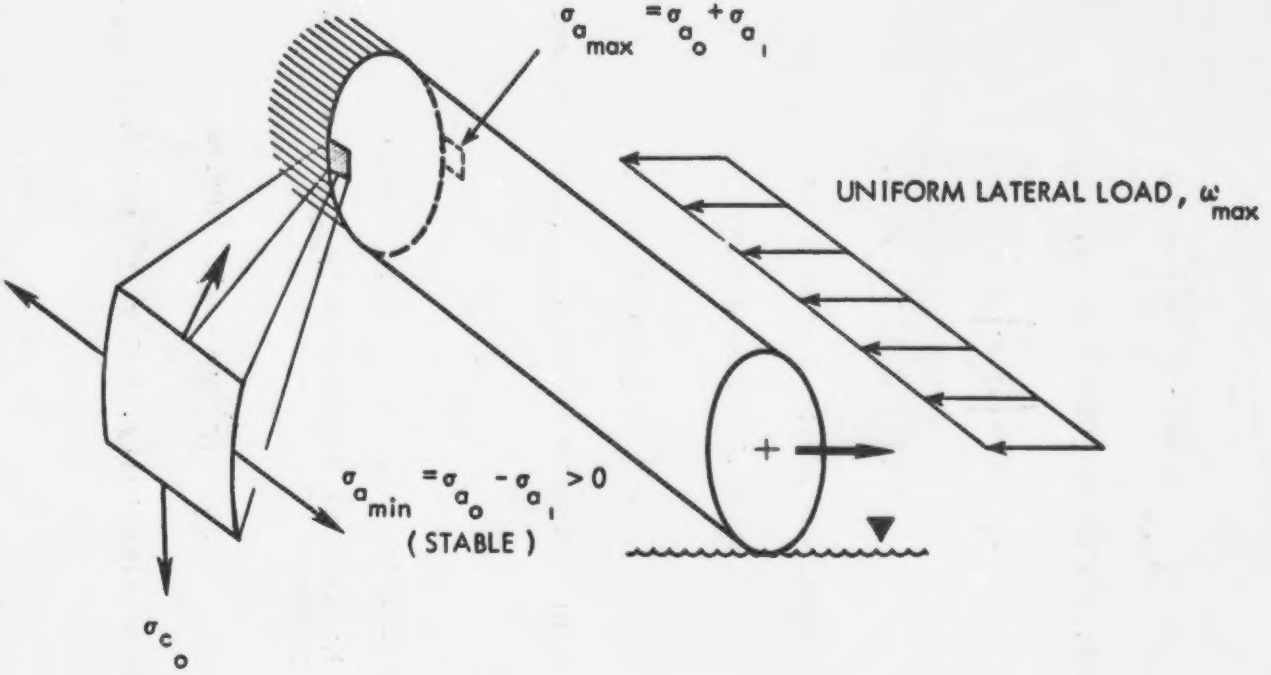
indicating that the inflatable section will probably buckle.

Case Two

Inflatable section floating with uniformly distributed horizontal load - cantilever with simple end support (see Figure D-2). For the cantilever with simple end support, the membrane stresses are given by the expression,

$$\sigma_{a_1} = \pm \frac{q\omega\ell_1{}^2 r}{128\ I} \quad . \qquad [13]$$

Superimposing the stress due to internal air pressure (Equation 1), maximum and minimum stresses are then:



$\sigma_{a_{max}} = \sigma_{a_o} + \sigma_{a_1}$
UNIFORM LATERAL LOAD, ω_{max}
+
$\sigma_{a_{min}} = \sigma_{a_o} - \sigma_{a_1} > 0$
(STABLE)
σ_{c_o}

Figure D-2. Inflatable section under uniformly distributed horizontal load - cantilever with simple end support.

$$\sigma_{a_{min}} = \frac{c\ pr}{2f} - \frac{q\omega \ell_1{}^2 r}{128\ I} \qquad [14]$$

and

$$\sigma_{a_{max}} = \frac{c\ pr}{2f} + \frac{q\omega \ell_1{}^2 r}{128\ I} \quad . \qquad [15]$$

Using the stability criteria (Equation 6),

$$\omega_s \leq 7.1 \left(\frac{c_1\ I}{f \ell_1{}^2} \right) p \qquad [16]$$

or

$$\leq (7.8 \times 10^{-2})\ p \quad . \qquad [17]$$

If the design pressure, 3.25 inches of water, is assumed

$$\omega_s \leq .253 \text{ pound/inch} \qquad [18]$$

or

$$\leq 3.49 \text{ pound/foot} \quad . \qquad [19]$$

Comparing to the estimate value ω_{max} (given by equation 11),

$$\omega_{max} < \omega_s \qquad [20]$$

indicating that the inflatable section is stable.

The maximum horizontal deflection (y_{max}) can be calculated by the expression

$$y_{max} = \frac{\omega \ell_1{}^4}{185\ EI} = .72 \text{ inches} \qquad [21]$$

where E = modulus of elasticity, 4.0×10^4 psi (see Appendix D, page 123).

Case Three

Inflatable section floating with uniformly distributed moment - cantilever support (see Figure D-3).

Membrane stresses arising from a uniformly distributed moment (m) on the inflatable section cause axial and circum-

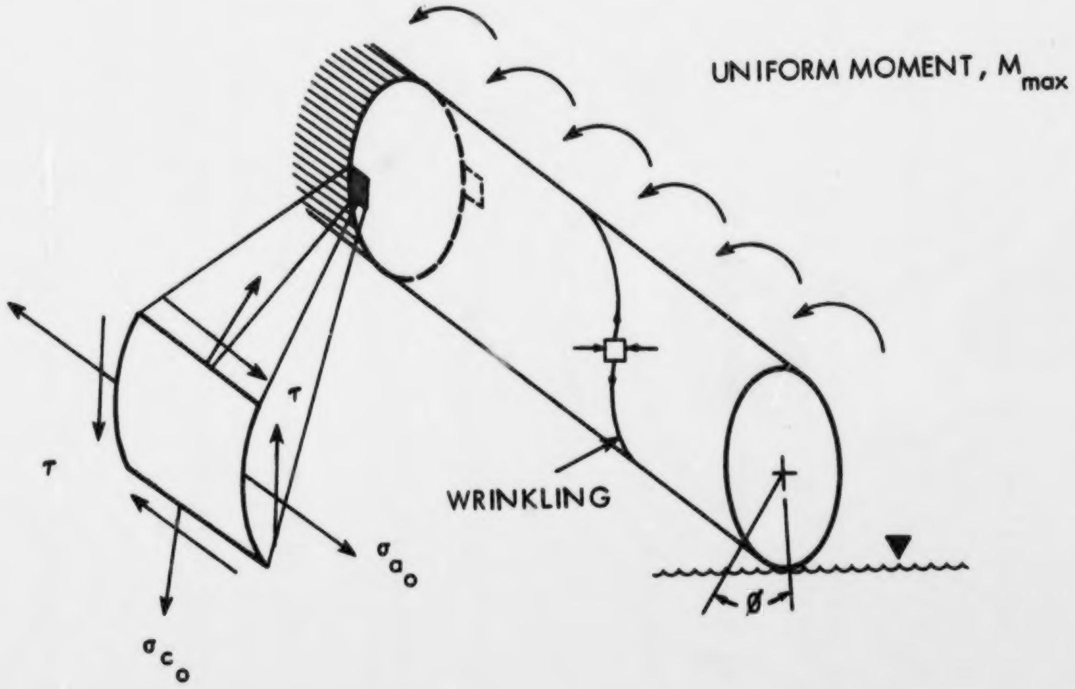

UNIFORM MOMENT, M_{max}
WRINKLING
τ
τ
σ_{a_0}
σ_{c_0}
$\emptyset$

Figure D-3. Inflatable section under uniformly distributed moment-cantilever support.

ferential shear stresses, as shown in Figure D-3. The stresses here do not contribute to buckling of the inflatable section, even when superimposed to the previous cases of lateral load*.

Angular deflection (φ) of the inflatable section (see Figure D-3) is given by the expression

$$\varphi = \frac{m\ell_1}{2GJ} \qquad [22]$$

where

φ = angular deflection, radians/inch

J = polar moment of inertia, 488 inches^4

G = shear modulus, 7.1×10^2 psi (see Appendix D, page 108).

Based on design guidelines in Appendix B (item 7), the limit on angular deflection was reckoned such that

$$\varphi_c < 1.4 \times 10^{-3} \text{ radians/inch} \quad . \qquad [23]$$

Combining Equations [22] and [23],

$$m_c < \pm 5.77 \text{ inch-pounds/inch} \qquad [24]$$

or

$$m_c < \pm 69.3 \text{ inch-pound/foot} \quad . \qquad [25]$$

Using the load estimates from Appendix D, page 121, a value of m_{max} was obtained. The following assumptions (worst case were used:

(1) The boom is deployed at θ = 90 degrees

(2) The tow speed is $V = 6$ knots (~10 feet/second)

(3) Moments are due to hydrodynamic drag and nozzle reactions ($\ell = 3/4''$, α = 45 degrees, h = 5 degrees)

such that

$$m_{max} = 10.8 \text{ inch-pounds/foot} \quad . \qquad [26]$$

---

*Wrinkling of the fabric, shown in Figure D-3, can occur along a helical plane whose angle is related to the initial distribution of membrane stress.

Comparing Equation [24] with Equation [26],

$$m_{max} < m_c$$

indicating that the inflatable section has adequate torsional stability.

WAVE CONFORMANCE

Based on a method similar to that described in Appendix D, page 105, calculations are made to indicate the tendency of the inflatable sections to conform to waves under static load conditions*.

Two wave conditions are described below:

Case One

High waves with wavelengths (λ) greater than the projected length of the inflatable section, $\ell_1 \cos\theta$ - cantilever support (see Figure D-4).

From the linear beam theory, the stress due to uniformly distributed vertical loads (ξ) with end load (i.e., end plate) (F) on cantilever, is calculated by the equation

$$\sigma_{a_2} = \pm \left[\frac{\xi \ell_1^2 r}{2I} + \frac{F \ell_1 r}{I} \right] \qquad [27]$$

where

σ_{a_2} = axial stress due to vertical load, pounds/inch^2

ξ = uniform vertical load, pound/inch

F = end load, 5 pounds.

Superimposing the axial stress due to internal air pressure (Equation 1), the maximum and minimum stresses are then

$$\sigma_{a_{min}} = \frac{c\,pr}{2t} - \left[\frac{\xi \ell_1^2 r}{2I} + \frac{F \ell_1 r}{I} \right] \qquad [28]$$

and

---

*Unsteady loading is not neglected.

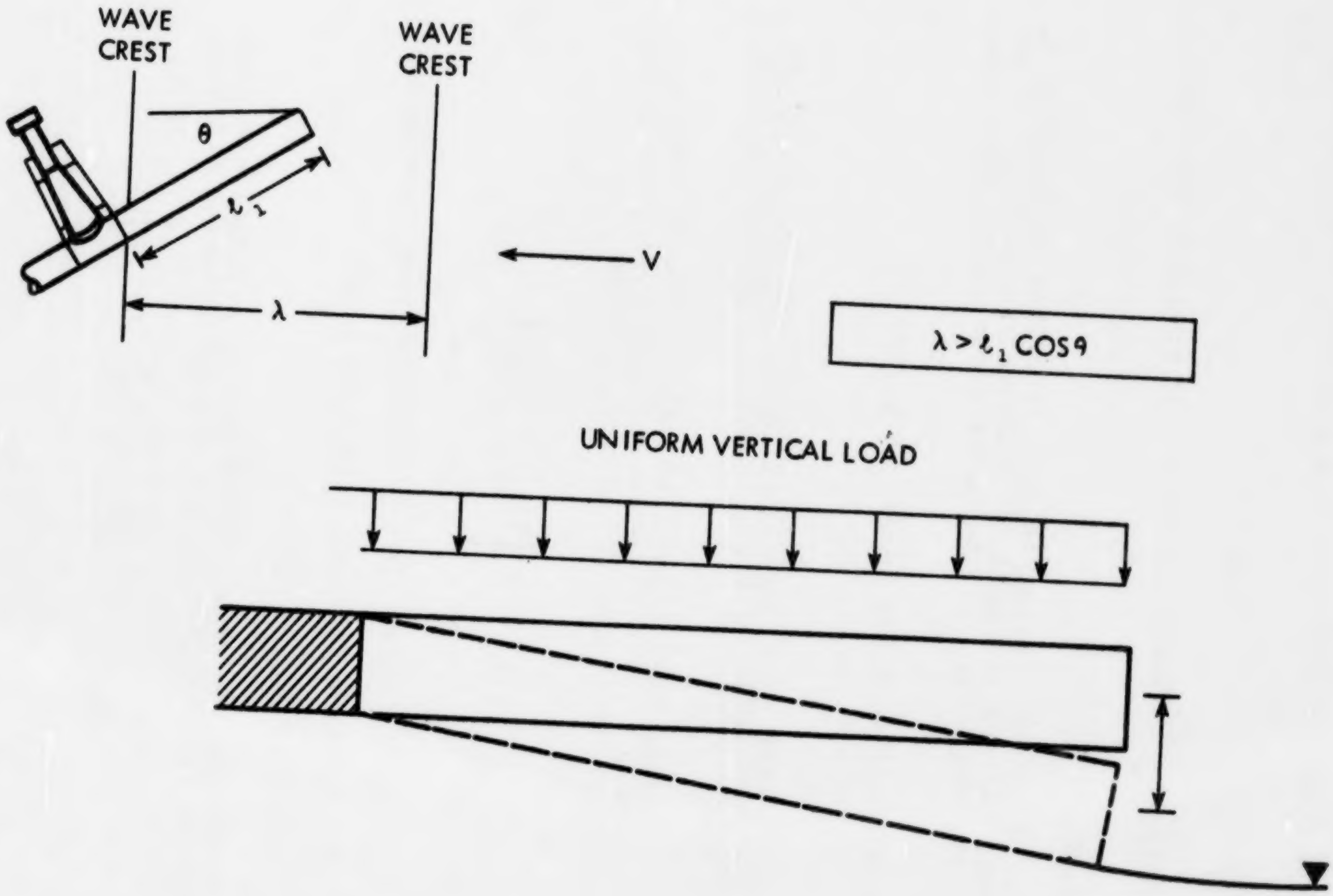

WAVE CREST
WAVE CREST
θ
ℓ_1
λ
V
$\lambda > \ell_1 \cos 9$
UNIFORM VERTICAL LOAD

Figure D-4. Conformance of inflatable section in waves of long wavelengths ($> \ell_1 \cos \theta$).

$$\sigma_{a_{max}} = \frac{c\ pr}{2f} - \left[\frac{\xi\ell_1{}^2 r}{2I} + \frac{F\ell_1 r}{I}\right] \quad . \qquad [29]$$

Based on the criteria like that in Equation [6],

$$\sigma_{a_{min}} \leq 0 \text{ (compliance criteria)} \qquad [30]$$

for the inflatable sections to contour with the free surface.

Therefore, combining Equation [6] and Equation [28], the minimum uniform vertical load requires (ξ_s) is

$$\xi_s \geq \left[\frac{cI}{f\ell_1{}^2}p - \frac{2F}{\ell_1}\right] \quad . \qquad [31]$$

If the end load F is 5 pounds,

$$\xi_s = 1.0 \times 10^{-2}\ p - 6.1 \times 10^{-2} \qquad [32]$$

and if the design air pressure is assumed to be 3.25 inches of water

$$\xi_s = -2.85 \times 10^{-2} \text{ pound/inch*} \qquad [33]$$

or

$$\geq -.34 \text{ pounds/foot} \quad . \qquad [34]$$

Using the load estimates from Appendix D, page 121, a value of ξ_{max} was obtained. The following assumptions were made:

(1) Lift forces are neglected

(2) Weight of the boom is 1.32 pound/foot

(3) An upward component of force is due to the nozzle reqction (ℓ = 3/4 inch, α - 45 degree)

such that

$$\xi_{max} = -.19 \text{ pound/foot} \qquad [35]$$

---

*The negative sign indicates an upward force.

since

$$\xi_{max} > \xi_s \qquad [36]$$

the inflatable sections will probably follow the free surface.

Case Two

High waves with wavelengths (λ) less than or equal to the projected length of the inflatable section, $\ell_1 \cos\theta$ (see Figure D-5).

Stress due to uniformly distributed vertical load is calculated by the equation

$$\sigma_{a_1} = \pm \frac{9\xi\ell_1{}^2 r}{128\ I} \qquad [37]$$

superimposing the stresses due to internal air pressure (Equation 1), the maximum and minimum stresses are then:

$$\sigma_{a_{min}} = \frac{c\ pr}{2f} - \frac{9\xi\ell_1{}^2 r}{128\ I} \qquad [38]$$

$$\sigma_{a_{max}} = \frac{c\ pr}{2f} - \frac{9\xi\ell_1{}^2 r}{128\ I} \quad . \qquad [39]$$

Combining Equations [30] and [38], the minimum uniform vertical load required for compliance is

$$\xi_s \geq \frac{7.11\ c\ Ip}{f\ell_1{}^2} \qquad [40]$$

or

$$\xi_s \geq 7.6 \times 10^{-2} \text{ pounds/inch} \qquad [41]$$

or

$$\xi_s \geq 9.2 \times 10^{-1} \text{ pound/foot} \quad . \qquad [42]$$

Hence, by comparing Equation [42] to Equation [35]

$$\xi_{max} < \xi_s \qquad [43]$$

it can be seen that compliance will probably not occur, at least under static condition.

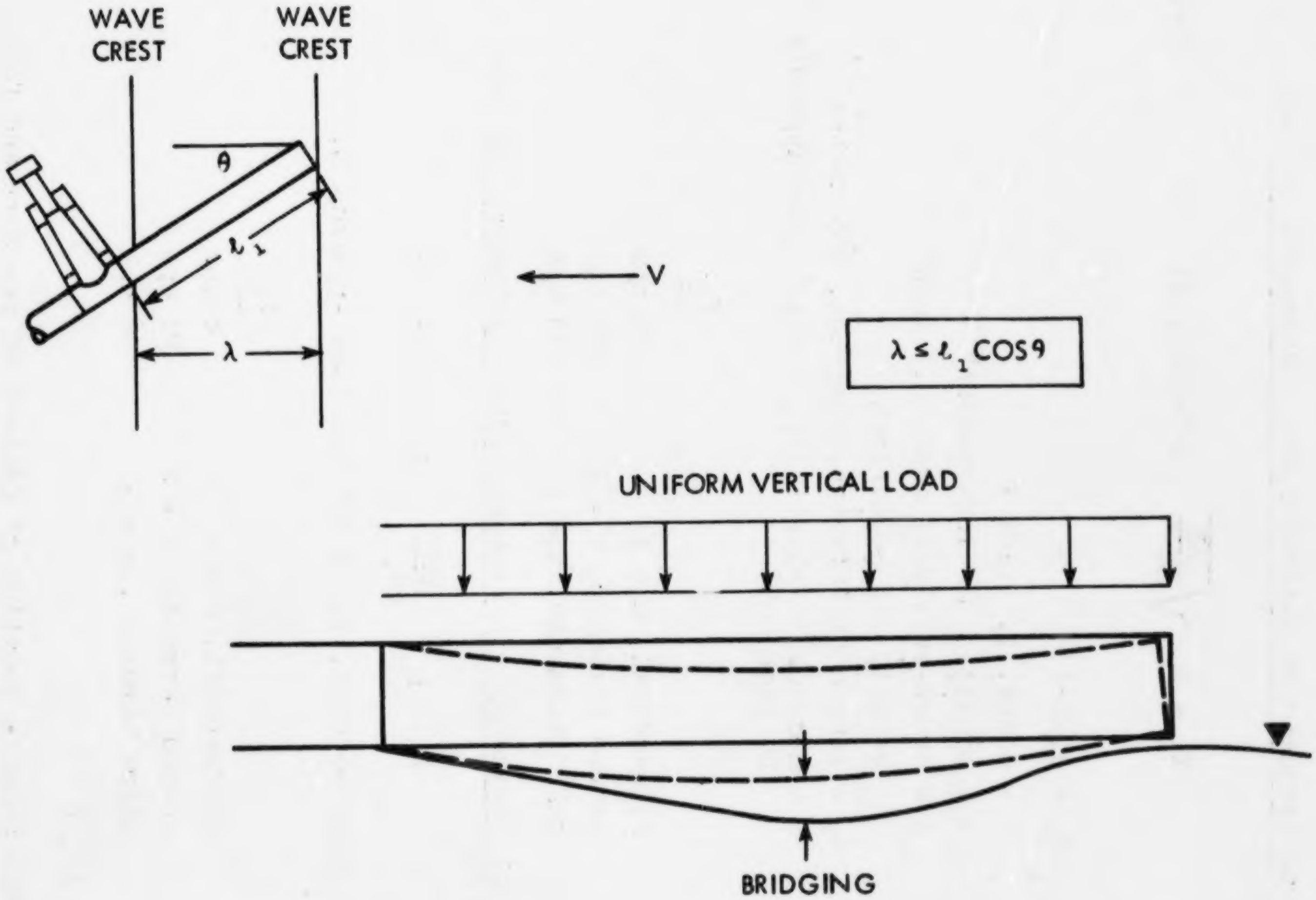

WAVE CREST
WAVE CREST
θ
ℓ_1
λ
V
$\lambda \leq \ell_1 \cos\theta$
UNIFORM VERTICAL LOAD
BRIDGING

Figure D-5. Conformance of inflatable section in waves of short wavelengths ($\leq \ell_1 \cos\theta$).

NATURAL FREQUENCIES

Natural frequencies lateral modes - undamped, f_L (see Figure D-6a)

$$f_L = B_n \sqrt{\frac{gAE}{m\ell_1^2}} \quad \text{(Reference 9)} \qquad [44]$$

where

$B_n = \frac{1}{2}(2n-1)$

n = modes, 1, 2 and 3

g = gravity, 386 inch/second^2

A = cross-sectional area, 2.3 inch^2

m = weight, .11 pound/inch

ℓ_1 = length of inflatable section, 165 inches

E = modulus of elasticity, 4×10^4 (see Appendix D, page 108)

	f_L
fundamental, n = 1	55 cps
second harmonic, n = 2	164 cps
third harmonic, n = 3	273 cps

Natural frequency - torsional modes - undamped, f_T (see Figure D-6b)

$$f_T = B_n \frac{gA6}{m\ell_1^2} \quad \text{(Reference 9)} \qquad [45]$$

where G = shear modulus, 7.1×10^2 psi (see Appendix D, page 108).

	f_L
fundamental, n = 1	8 cps
second harmonic, n = 2	21 cps
third harmonic, n = 3	38 cps

ESTIMATED LOADS

The approximate location of centers of pressure and force are shown in Figure D-7.

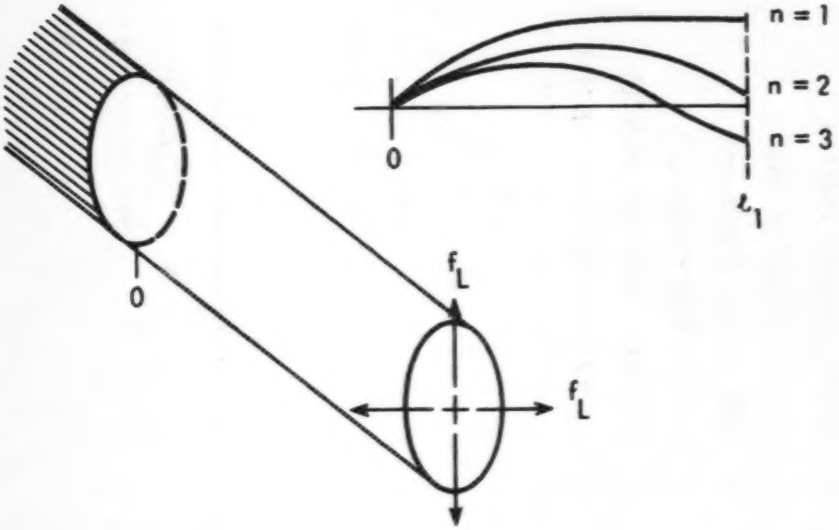

n = 1
n = 2
n = 3
0
ℓ_1
0
f_L
f_L

Figure D-6a. Natural frequency - lateral modes (undamped).

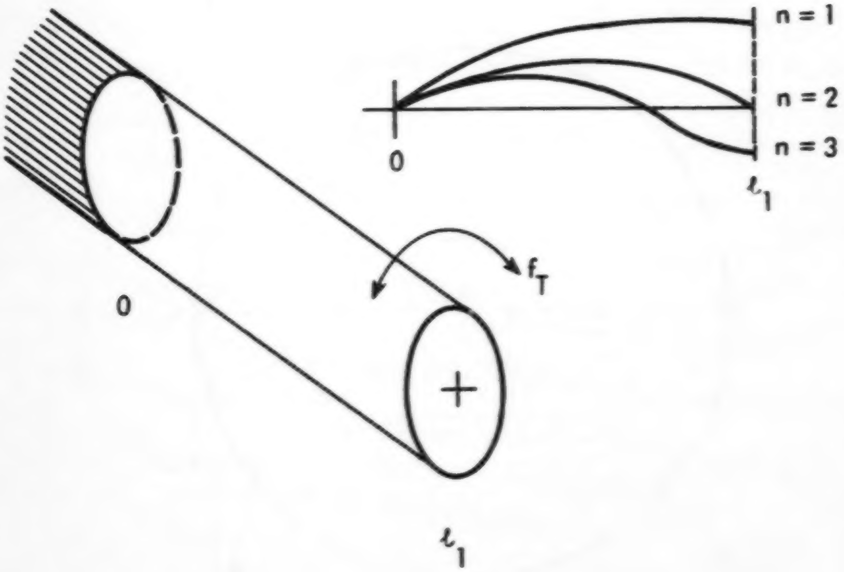

n = 1
n = 2
n = 3
0
ℓ_1
0
f_T
ℓ_1

Figure D-6b. Natural frequency - Torsional mode (undamped).

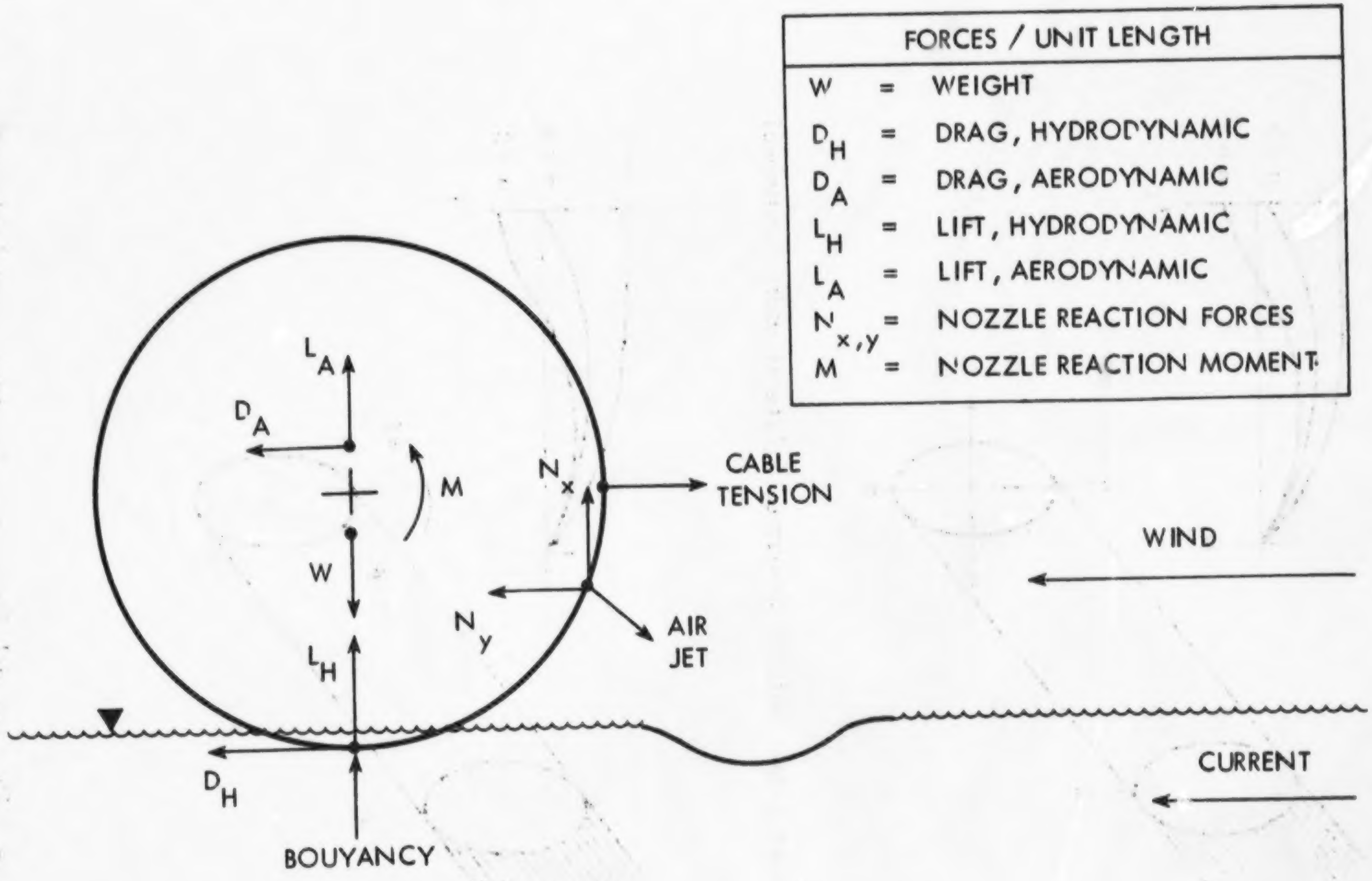

FORCES / UNIT LENGTH
W = WEIGHT
D_H = DRAG, HYDRODYNAMIC
D_A = DRAG, AERODYNAMIC
L_H = LIFT, HYDRODYNAMIC
L_A = LIFT, AERODYNAMIC
N_x,y = NOZZLE REACTION FORCES
M = NOZZLE REACTION MOMENT
L_A
D_A
M
W
N_x
N_y
L_H
D_H
CABLE TENSION
AIR JET
WIND
CURRENT
BOUYANCY

Figure D-7. Estimated loads on inflatable section (per unit length).

Weight, W

$$W = 2\pi\rho_f r \text{ (pounds/foot)} \qquad [46]$$

where

r = boom radius, 1 foot

ρ_f = fabric density, .21 pound/foot^2

$W = 2\pi\ (.21)(1) = 1.32$ pound/foot

Drag, Hydrodynamic, D_H

$$D_H = \frac{C_{D_H} \rho_w S V_w^{\,2}}{2} \text{ (pounds/foot} \qquad [47]$$

where

C_{D_H} = drag coefficient, 4.6×10^{-3} (Reference 10)

ρ_w = water density, 62.4 pound/foot^2

V_w = tow speed, normal foot/second

S = wetted area

Assuming still water conditions

$$S = \frac{\pi R}{90}\left[\cos^{-1}\left(1 - \frac{d}{r}\right)\right] \qquad [48]$$

where

d = boom draft, .08 foot (estimated)

r = boom radius, 1 foot.

Combining Equations [2] and [3]

$$D_H = 3.42 \times 10^{-3}\ V^2 \text{ pounds/foot.}$$

Drag, Aerodynamic, D_A

$$D_A = \frac{C_{D_A} \rho_A A_o V_A^{\,2}}{2g_c} \text{ (pound/foot)} \qquad [49]$$

where

C_{D_A} = drag coefficient, 4.0×10^{-1} (Reference 10)
ρ_A = air density, .075 pounds/foot^3
A_o = projected area, 2 foot^2/foot
V_A = relative air speed, normal, foot/second

$$D_A = 9.3 \times 10^{-4} V_A^2 \text{ (pound/foot)} \qquad [50]$$

where

.2 = lift to drag ratio, (Reference 10).

Lift, L

$$L = .2 D \qquad [51]$$

Nozzle Forces, N_x, N_y

$$N_x = 1.4 \times 10^{-2} \frac{\rho_w g p \ell}{g_c} \cos \alpha \text{ (pound/foot)} \qquad [52]$$

$$N_y = 1.4 \times 10^{-2} \frac{\rho_w g p \ell}{g_c} \sin \alpha \text{ (pound/foot)} \qquad [53]$$

where

ρ_w = density of water, 62.4 pound/foot^3
p = boom pressure, inches of water
ℓ = nozzle throat, inches
α = nozzle impingement angle with free surface, degrees

Nozzle Moment, M

$$M = N_2 \left(\sqrt{23+22h-h^2}\right) - N_x (11-h) \; \frac{\text{inch pounds}}{\text{foot}} \qquad [54]$$

where

h = nozzle height, inches. Note that the boom draft is assumed to be 1 inch. A positive value of M indicates moments of tendency to rotate the air jet away from the free surface . A negative value of M indicates moments of tendency to rotate the air jet toward the free surface.

DETERMINATION OF MODULUS OF ELASTICITY AND SHEAR MODULUS

Modulus of Elasticity, E

The modulus of elasticity was determined by evaluating the load/deflection characteristics of a segment of the inflatable section (without the nozzle) constructed with the selected fabric. The results shown in Figure D-8 indicate linear behavior up to the point of local buckling or wrinkling of the fabric. In this range, the ratio of load to deflection (P/δ_1) is about 6.15 pound/inch. The modulus of elasticity determined from beam theory (Reference 8) is

$$E = \frac{P}{\delta_1} \left(\frac{\ell_2{}^3}{3I} \right) = 4 \times 10^4 \text{ psi} \quad . \qquad [55]$$

Shear Modulus, G

The determination of shear modulus (G) was carried out in a similar way. The results given in Figure D-9 reveal linear load/deflection behavior up to the point of wrinkling. The ratio M/φ_1 is about 7690 inch pounds per radian within this range. Using the beam theory, the shear modulus is

$$G = \frac{M}{\varphi_1} \left(\frac{\ell_2}{J} \right) = 7.1 \times 10^2 \text{ psi} \quad . \qquad [56]$$

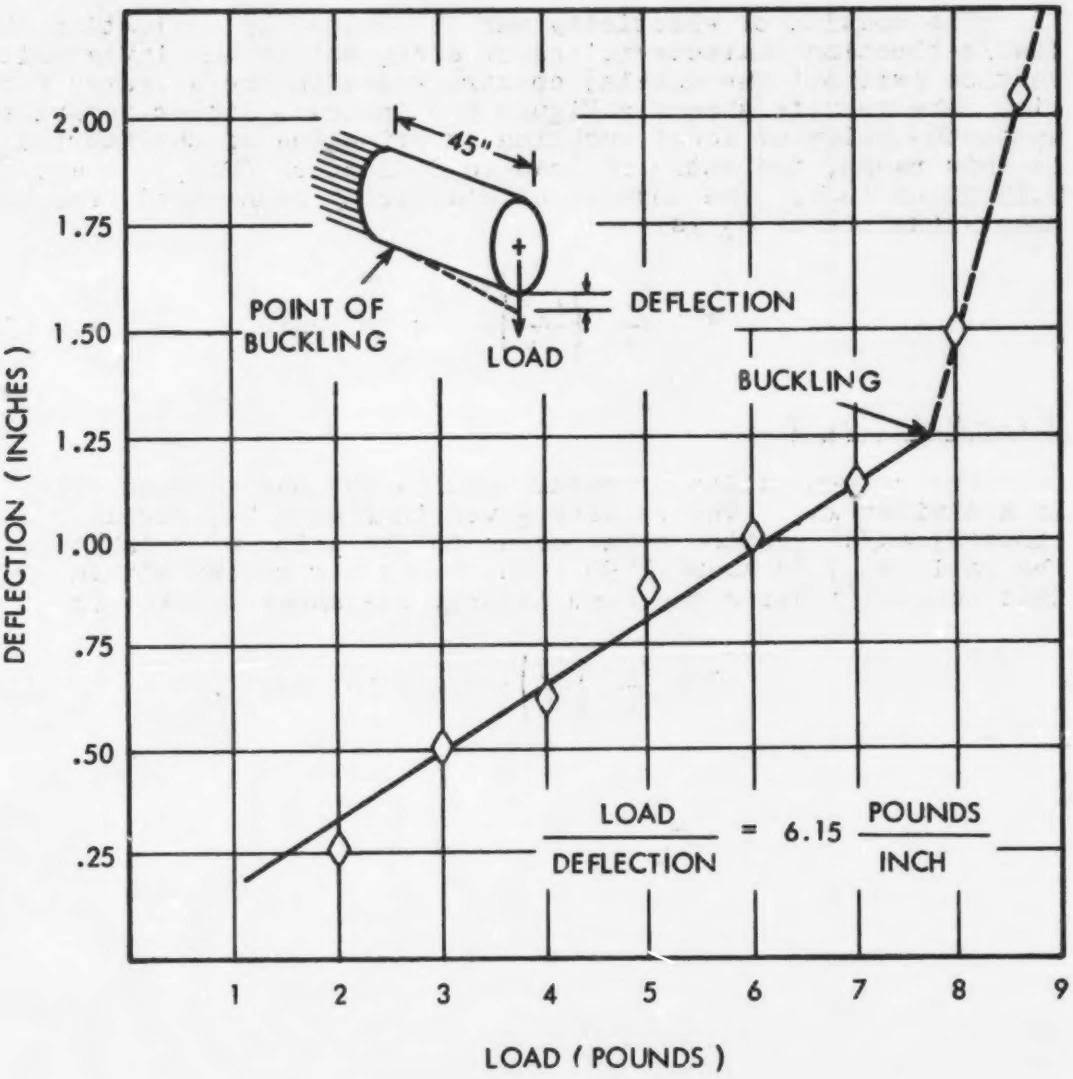


Figure D-8. Load/deflection of inflatable section for determination of modulus of elasicity.

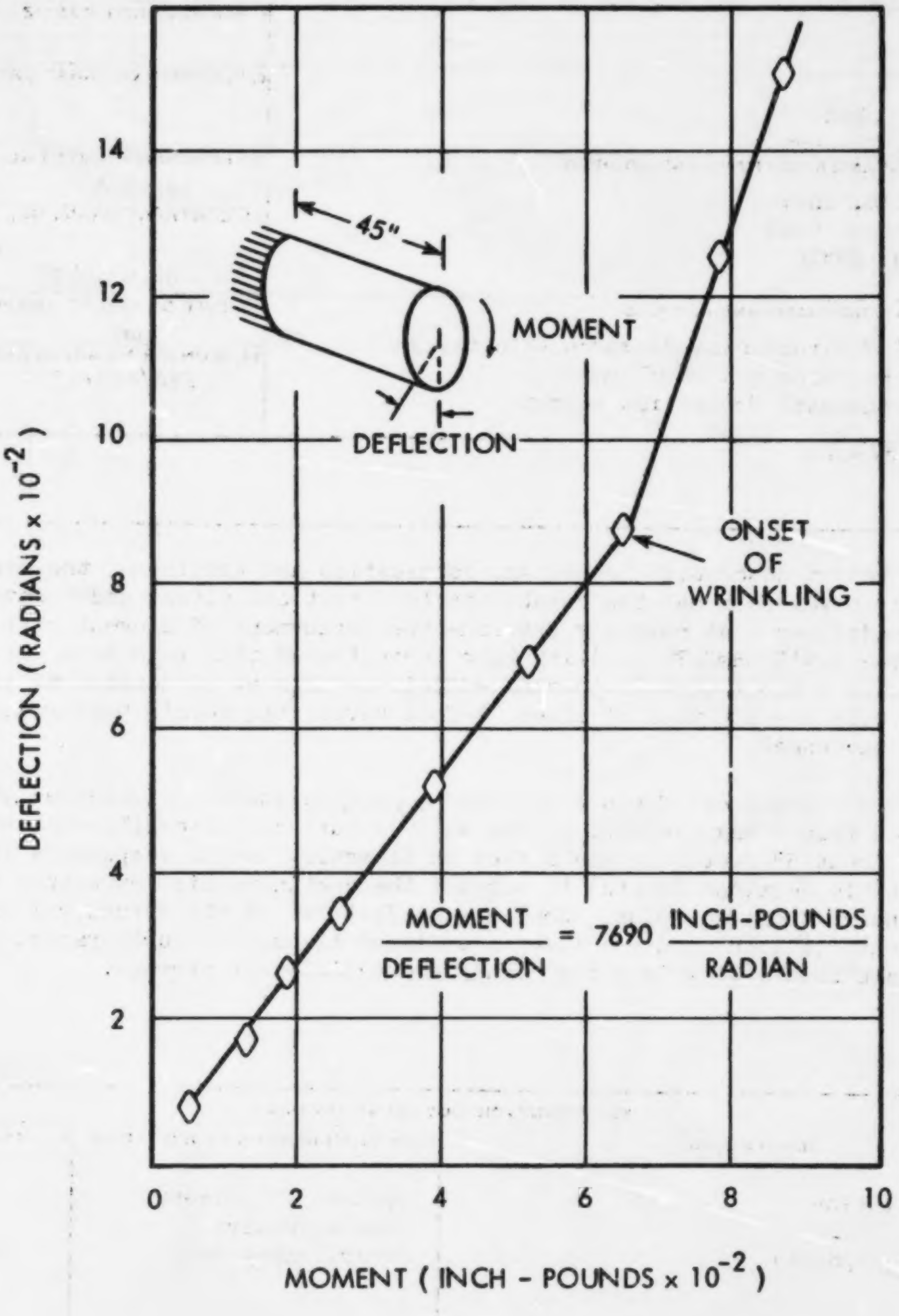


Figure D-9. Load/deflection of inflatable section for determination of shear modulus

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